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ORIGINAL RESEARCH

The Effect of Thermal Cycling and Cyclic Loading on The Flexural Strength of Milled PMMA Versus 3D Printed PEEK as a Provisional Restorative Restoration

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Background: Temporary restorations play a crucial role in oral rehabilitation. The development of CAD/CAM technology and 3D printing has expanded the use of polymethyl methacrylate (PMMA) and polyetheretherketone (PEEK) in the fabrication of provisional restorations. While both materials are widely used, their mechanical behavior under simulated long-term clinical conditions remains largely unununderstood.

Aim: This study aims to compare the flexural strength of CAD/CAM milled PMMA and CAD/CAM 3D-printed PEEK provisional crowns that were subjected to thermocycling and cyclic loading, simulating the aging protocols designed to replicate long-term clinical use.

Materials and Methods: A total of 54 provisional crowns (n = 27 per group) were fabricated from PMMA and PEEK. All specimens underwent an aging protocol consisting of 2500 thermal cycles (5°C–55°C) and 600,000 mechanical loading cycles (50 N, 1.6 Hz). Flexural strength was assessed using a universal testing machine. Fracture load values were analyzed using descriptive statistics and compared using the Mann–Whitney *U*-test ($p < 0.05$).

Results: PEEK crowns exhibited significantly higher mean fracture load values (2.441 ± 0.573 kN) than PMMA (1.860 ± 0.517 kN), with a statistically significant difference ($p = 0.0004$). PEEK specimens demonstrated consistent mechanical performance and ductile failure patterns, while PMMA crowns showed brittle fractures and greater variability.

Conclusion: 3D printing PEEK provisional crowns demonstrated superior flexural strength compared to milled PMMA under simulated aging conditions. PEEK represents a promising material for long-term provisional use, particularly in high-load clinical scenarios.

Keywords: PEEK, PMMA, flexural strength, thermocycling, CAD/CAM, 3D printing, fracture resistance

Introduction

The development of digital dentistry has transformed the traditional restorative and prosthodontic workflows through the integration of computer-aided design and computer-aided manufacturing (CAD/CAM) systems.[1] These technologies enable the accurate and reproducible fabrication of dental restorations.[2] CAD/CAM processes can be classified into two main categories: subtractive manufacturing, where restorations are milled from pre-polymerized blocks, and additive manufacturing, also known as 3D printing, which builds objects layer by layer from digital designs.[3] The flexibility and speed of additive processes have prompted increased interest in applying 3D printing to provisional restorations and other prosthodontic components.[4,5]

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In clinical dentistry, provisional restorations play a crucial role in prosthetic rehabilitation. They can be used over teeth or implants for a variable amount of time during the intermediate phase before rehabilitation with permanent.[6,7] They are promoting the treatment procedure while maintaining esthetics, function, and occlusion. In long-term clinical scenarios, provisional restorations are necessary before final extension of functional loading and thermal variation in the oral environment.[8,9] Therefore, selecting appropriate materials for provisional crowns that are biocompatible and esthetically acceptable creates the foundation for sufficient mechanical resilience, especially in posterior regions that are exposed to high occlusal forces.[10]

Polymethyl methacrylate (PMMA) and polyether ether ketone (PEEK) are commonly used materials for provisional crowns and are increasingly adopted in CAD/CAM workflows.[11] These materials provide strength, dimensional stability, and marginal stability, as well as functional occlusal load. PMMA has been the material of choice for decades due to its favorable aesthetics, affordability, and ease of manipulation.[12] This acrylic composite is formed from an exothermic reaction (polymerization) by mixing a powder and a liquid component in a 2:1 ratio.[13] PMMA also exhibits favorable mechanical properties compared to conventionally processed PMMA in its CAD/CAM-milled form, including higher flexural strength and improved surface uniformity.[14] However, it has several drawbacks, including dimensional instability, reduced fatigue resistance, and a tendency toward brittle fracture, which limit its performance under long-term intraoral conditions. The flexural strength is a mechanical property that measures a material's resistance to breaking or permanent deformation when subjected to bending forces. This property is critical for full coverage crowns because daily masticatory function exposes the restoration to repetitive bending stresses. Materials with flexural strength, such as PEEK, are less likely to crack or fail under load, while PMMA has low flexural strength so that it may fracture more readily under the same conditions.[15,16]

On the other hand, PEEK is a high-performance thermoplastic material known for its excellent fracture toughness, dimensional stability, and favorable biocompatibility.[17] With an elastic modulus close to that of cortical bone and high resistance to chemical and thermal degradation, PEEK has been increasingly used in dental implantology and fixed prosthodontics[18,19] However, PEEK has some aesthetic limitations, such as low translucency, which requires veneering in the anterior zone.[11,20] PEEK's mechanical superiority makes it a strong candidate for long-term provisional crowns, particularly when 3D printing enables more customized and cost-efficient fabrication.[21,22]

The long-term success of any provisional restoration depends on its ability to resist masticatory loads and variations in oral temperature over time.[6] Flexural strength is a widely accepted indicator of fracture resistance under compressive stress and is particularly relevant for assessing crown materials under simulated functional loads.[23,24] Another indicator, including thermocycling and cyclic loading, is the use of established in vitro aging techniques that simulate the effects of intraoral temperature fluctuations and repetitive chewing forces, respectively[25,26] These protocols provide insight into how restorative materials may degrade or fail under real-life oral conditions.[27]

However, several studies have investigated the mechanical characteristics of PMMA and PEEK. Limited studies directly compare the flexural strength, thermal cycling, and cyclic loading of two materials in provisional crown restorations.[28] This study aims to compare the flexural strength of CAD/CAM milled PMMA and CAD/CAM 3D-printed PEEK provisional crowns that were subjected to thermocycling and cyclic loading, simulating the aging protocols designed to replicate long-term clinical use.

Materials and Methods

Sample Size and Study Design

A power analysis was conducted to ensure statistical validity, with a significance level (α) of 0.05 and statistical power of 80%. Based on this analysis, a total of 54 crown specimens were allocated into two groups (n = 27 per group): Group 1 consisted of milled CAD/CAM PMMA, and Group 2 consisted of 3D-printed PEEK. These sample sizes were determined to detect clinically significant differences in flexural strength, considering potential variability after aging protocols designed to simulate long-term clinical use.

Tooth Preparation

A typodont maxillary right first molar was prepared following standardized tooth preparation guidelines for full coverage crowns to receive PEEK or PMMA crowns. The preparation included a 1.5 mm occlusal reduction (2 mm on the functional palatal cusp), a continuous circumferential shoulder finish line (1 mm width), and an 8° axial taper. Parallelism was verified using a surveyor-mounted handpiece, and occlusal clearance was confirmed against opposing casts.

Digital Workflow and Fabrication

The prepared typodont of the first molar was digitized using an intraoral scanner (Trios, 3Shape, Copenhagen, Denmark). A full-contour crown was designed using dental CAD software (Dental Designer; 3Shape, Copenhagen, Denmark), and STL files were exported for fabrication (Figure 1). The PMMA group was milled using a 4-axis milling machine (Ceramill Motion 2, Amann Girrbach, Koblach, Austria) under dry conditions with a spindle speed of 20,000 RPM, a feed rate of 800 mm/min, and 1.5 mm carbide burs. PMMA crowns were fabricated from *Telio CAD* blocks (Ivoclar Vivadent, Schaan, Liechtenstein; Shade A2). The PEEK group was 3D-printed using the NextDent 5100 printer (3D Systems, Rock Hill, SC, USA) at a 50 µm layer thickness using *BioHPP* material (Bredent GmbH, Senden, Germany; Shade: Dentin Medium). Post-processing included isopropyl alcohol rinsing, support removal, and UV curing in the LC-3DPrint Box unit (NextDent, 3D Systems). The PEEK crowns provided favorable esthetics, excellent biocompatibility, and required minimal polishing. PMMA crowns served effectively as provisional esthetic restorations and were suitable for multi-unit bridges.

Specimen Mounting

Crowns were embedded in auto-polymerizing acrylic resin (Technovit 4000; Heraeus Kulzer, Wehrheim, Germany) within cylindrical molds (30 mm diameter). A silicone putty index (condensation silicone, type C) ensured consistent positioning during resin polymerization. Specimens were cured for 24 hours under controlled conditions and subsequently removed for testing.

Aging Protocol

To simulate clinical aging, specimens underwent sequential thermal cycling and cyclic loading. Thermal cycling was performed for 2500 cycles (5°C to 55°C, 30-second dwell times), followed by mechanical loading using a dual-axis machine (Power Electronics Co., Amman, Jordan). A force of 50 N was applied at 1.6 Hz for 600,000 cycles, equivalent to approximately 2.5 years of mastication.

In this method, the samples are embedded in alternating cold and hot water baths to simulate the temperature cycles found in the oral cavity. It is performed aiming to create thermal strains at the bonding interface by thermal changes in water baths between 5 and 55 °C[26]

Flexural Strength Testing

Specimens were secured in a universal testing machine at a 90° angle relative to the loading jig. A steel indenter (2.5 mm diameter) delivered a compressive load to the central fossa at a crosshead speed of 0.5 mm/min until fracture. Following testing, failure modes were assessed visually without magnification. Fractures were classified based on observable features, including crack propagation, location, and fracture extent.

Statistical Analysis

Descriptive statistics were calculated for each group, including the mean, standard deviation, median, range, and interquartile range of fracture load values. The data was not normally distributed according to the Shapiro–Wilk test. Therefore, the Mann–Whitney *U*-test was used to compare fracture resistance between the PMMA and PEEK groups. A p-value of less than 0.05 was considered statistically significant. All analyses were performed using GraphPad Prism version 8.0.2 (GraphPad Software, San Diego, CA, USA).

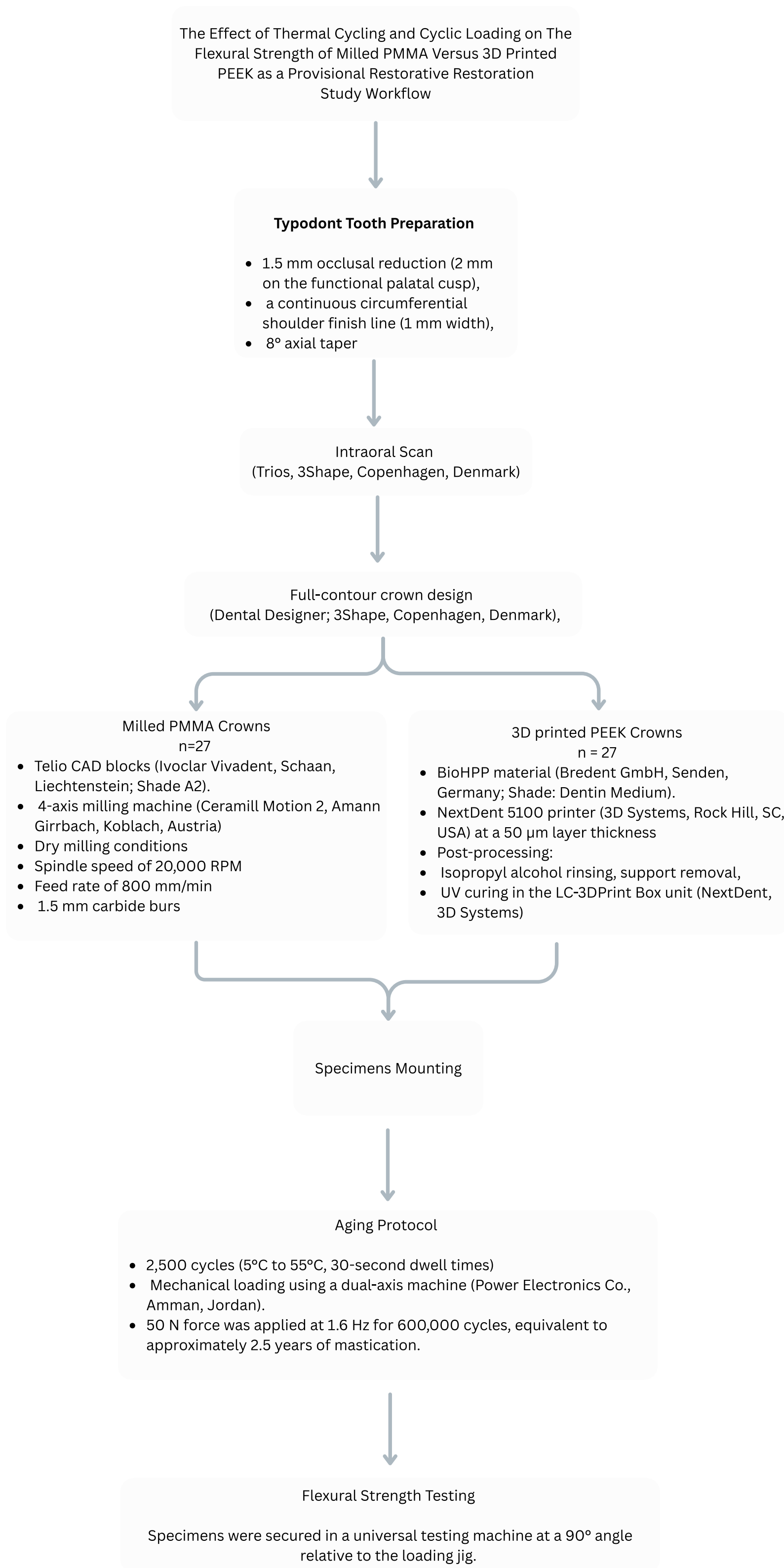

Figure 1 A flowchart of the 3D printing process.

Table 1 Fracture Load Values (kN) for CAD/CAM Milled PEEK and PMMA Provisional Crowns. PEEK Exhibited Higher Mean and Median Fracture Resistance and Lower Variability Than PMMA

Maximum Load (Fracture Load (KN))	PEEK (n = 26)	PMMA (n = 25)
Mean ± SD (kN)	2.441 ± 0.573	1.860 ± 0.517
Median (kN)	2.518	1.816
Min – Max (kN)	1.016–3.508	0.836–3.264
Interquartile Range	0.605	0.624

Result

The Fracture Load Values

The fracture load of each sample of PEEK and PMMA crown samples was presented in Table 1. The reported fracture load values represent the performance of specimens after undergoing standardized thermal and mechanical aging. Fracture load values revealed that PEEK crowns exhibited higher flexural strength compared to PMMA crowns. The mean fracture load was 2.441 ± 0.573 kN for PEEK and 1.860 ± 0.517 kN for PMMA (Table 1). Median values were 2.518 kN and 1.816 kN, respectively, while the fracture load ranged from 1.016 to 3.508 kN for PEEK and 0.836 to 3.264 kN for PMMA. The interquartile range (IQR) was comparable between groups: 0.605 kN for PEEK and 0.624 kN for PMMA.

The PEEK group exhibited significantly higher fracture resistance compared to PMMA. The fracture load range for PEEK was 1.016 to 3.508 kN, with most values distributed above 2.0 kN. In contrast, PMMA specimens ranged from 0.836 to 3.264 kN, showing greater variability and a larger proportion of lower-strength values.

Figure 2 illustrates the distribution of fracture loads. The findings reveal a narrower interquartile range in the PEEK group, indicating more consistent mechanical performance. Although both groups included high-end outliers, the PMMA

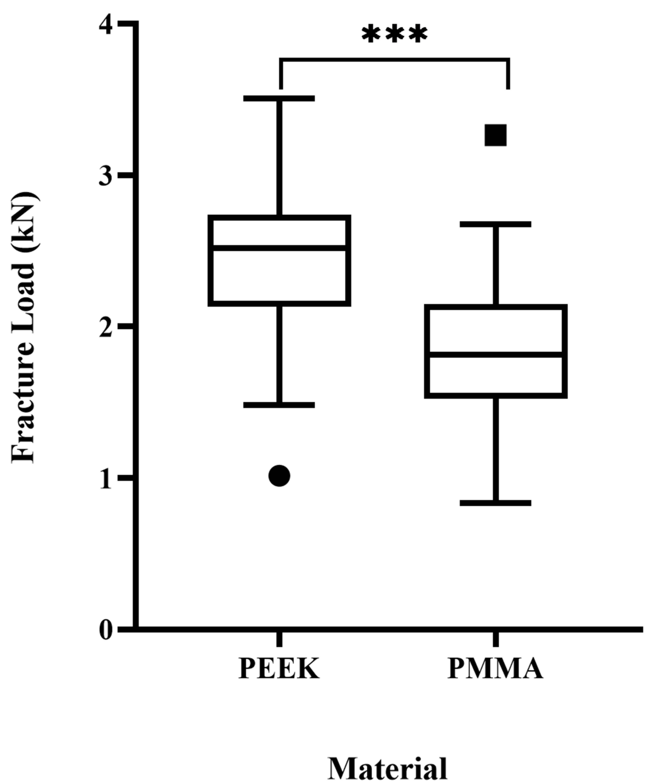

Figure 2 Boxplot comparison of fracture load values (kN) between milled PEEK and PMMA provisional crowns. The PEEK group exhibited significantly higher fracture resistance ($p < 0.001$) with reduced variability and a higher median compared to PMMA. ***means that p < 0.001.

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Table 2 Mann–Whitney *U*-Test Comparing Fracture Load of PEEK Vs PMMA

Comparison	Median (kN) – PEEK	Median (kN) – PMMA	U-value	*p*-value	Difference (Hodges–Lehmann)
PEEK vs PMMA	2.518 (n = 26)	1.816 (n = 25)	141.5	0.0004	–0.66 kN

Table 3 Summary of Failure Modes Observed in PEEK and PMMA Specimens Following Fracture Load Testing

Material	Dominant Failure Mode	Frequency (n)	Description
PMMA	Brittle fracture	25 / 25	Complete visible fracture along the central fossa or the marginal ridge
PEEK	Indentation (no fracture)	26 / 26	Localized occlusal surface indentation without crack propagation

group showed greater scatter, particularly in the lower quartile. These findings confirm that PEEK exhibits superior fracture resistance and greater mechanical reliability compared to PMMA under identical testing conditions.

A Mann–Whitney *U*-test revealed a statistically significant difference in fracture load between the two groups (U = 141.5, p = 0.0004), as shown in Table 2. The median difference, estimated using the Hodges–Lehmann method, was –0.66 kN, indicating a preference for PEEK.

Failure Mode Analysis

In addition to quantitative differences, the two materials exhibited distinct failure modes. All PMMA specimens underwent visible brittle fractures, typically along the central fossa or marginal ridges. In contrast, PEEK specimens did not fracture underloading; instead, a localized indentation was observed on the occlusal surface, with no crack propagation or catastrophic failure. Table 3 summarizes the failure modes observed in PEEK and PMMA specimens following fracture load testing (See Supplementary Figures 1 and 2 showing failure modes for both PEEK and PMMA).

These results indicate that, under identical loading conditions, PEEK not only demonstrates superior fracture resistance but also exhibits a more ductile and resilient failure pattern compared to the brittle fracture behavior of PMMA.

Discussion

This study examines the fracture resistance of CAD/CAM-fabricated PEEK and PMMA crowns, materials commonly employed in both provisional and definitive prosthodontic applications. The results demonstrated that PEEK exhibited significantly higher fracture load values (mean 2.441 ± 0.573 kN) compared to PMMA (mean 1.860 ± 0.517 kN), with the difference being statistically significant (p = 0.0004). These findings confirm the hypothesis that material composition has a substantial impact on the mechanical performance of dental restorations under compressive stress. From a clinical perspective, PEEK may undergo controlled deformation under occlusal stresses. This ductile failure behavior is advantageous because it allows the material to deform under occlusal forces rather than fracture catastrophically. So PEEK provisional crowns are less susceptible to sudden failure during mastication, delivering greater reliability in high-load posterior locations and reducing the need for emergency replacement.[29]

Our results align with those of previous studies, demonstrating that PEEK exhibits excellent mechanical performance and environmental resistance, and remains functionally unaffected under extreme conditions, such as high or low temperatures.[11] These superior mechanical properties are primarily due to its semi-crystalline polymeric substance, with high-performance engineering thermoplastic, a melting point of around 340 °C, and a glass transition temperature of about 143 °C, which enhances its outstanding thermal and mechanical stability.[28] 3D-printed PEEK exhibits excellent flexural and tensile strength, and parameters such as printing temperature and speed can affect its mechanical properties.[29] Limaye et al found that 3D-printed PEEK has advantages over milled PEEK, particularly in terms of cell adhesion and biocompatibility, although it exhibits lower mechanical resistance.[30] Using a 3D-printed molding technique enables the selection of appropriate printing parameters, such as speed, printing temperature, deposition direction, and

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layer thickness, allowing for modification of the mechanical properties of the final PEEK restoration.[31,32] The literature aligns with our findings, which demonstrate that 3D-printed PEEK is superior to milling PMMA.

In comparison, PMMA had the weakest performance. However, PMMA is widely utilized for provisional restorations due to its favorable esthetic properties, cost-effectiveness, and ease of manipulation. This study and previous studies argue that PEEK has better flexural strength and hardness properties than PMMA.[33–35] Shrivastava et al demonstrate that PEEK has superior fracture resistance to PMMA, making it a significant candidate for dental use. They noted a highly significant ($p < 0.05$) difference in the flexural strength values between PMMA and PEEK. The mean flexural strength of PEEK (183 MPa) was found to be greater than that of PMMA (84 MPa). Muhsin et al also concluded that the mechanical properties of PEEK materials are better than those of PMMA. Further, Mendes et al noted that the crowns made with the PEEK material presented the best fracture resistance compared with those made with composite resin and PMMA.[23]

This experiment also incorporated thermocycling, a standard artificial aging method to mimic oral conditions and thermal stresses caused by ingestion of hot and cold substances.[26,36] The protocol of 5000 cycles simulating five years of clinical use aligns with other studies assessing long-term material performance.[36] The durability of PEEK post-thermocycling suggests superior resistance to hydrothermal aging, further validating its potential as a durable restorative material. Previous studies have shown that PEEK exhibits significantly higher flexural strength compared to other provisional materials, even after aging and thermocycling. Notably, while aging and thermal stress reduced its strength by approximately 44%, PEEK still maintained superior mechanical performance, supporting its use in long-span provisional restorations for full-mouth rehabilitations.[37]

In clinical dentistry, the selection of restorative material should strike a balance between aesthetics, mechanical reliability, and biocompatibility. While PMMA may remain appropriate for short-term provisional applications, particularly in esthetically sensitive cases due to its translucency, PEEK offers a compelling alternative for situations requiring higher load-bearing capacity and long-term durability, especially in posterior regions and implant-supported prostheses.[18]

Conclusion

In conclusion, this study aligns with previous literature that supports the mechanical superiority of PEEK over PMMA in prosthodontic applications. Future research should further evaluate the long-term fatigue behavior, bonding characteristics, and esthetic integration of veneered PEEK crowns under dynamic loading and real-time clinical conditions.

Data Sharing Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

All authors made a significant contribution to the work reported, whether in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare that there is no conflict of interest regarding the publication of this article.

References

1. Lamasanu V, Nicolaiciuc O, Constantin V, et al. From design to restoration: cad/cam in contemporary dental prosthodontics. *Rom J Med Dent Educ*. 2025;14(1).
2. Alageel O, Wazirian B, Almufleh B, Tamimi F. Fabrication of dental restorations using digital technologies: techniques and materials. *Digit Restor Dent*. 2019;55–91.
3. Alsawaf AFB. *Computer Aided Design/Computer Aided Manufacturing and 3D Printing for Fabrication of Complete Dentures*. University of Baghdad; 2023.
4. Dimitrova M, Vlahova A, Kalachev Y, Zlatev S, Kazakova R, Capodiferro S. Recent advances in 3D printing of polymers for application in prosthodontics. *Polymers*. 2023;15(23):4525. doi:10.3390/polym15234525
5. Saini RS, Gurumurthy V, Quadri SA, et al. The flexural strength of 3D-printed provisional restorations fabricated with different resins: a systematic review and meta-analysis. *BMC Oral Health*. 2024;24(1):66. doi:10.1186/s12903-023-03826-x
6. Heboyan AG, Movsisyan NM, Khachatryan VA. Provisional restorations in restorative dentistry. *World Sci*. 2019;3:11–17.
7. Abdelmohsen N, Bourauel C, Elshazly TM. Interim fixed dental prostheses fabrication techniques and factors affecting their success: a narrative review. *Oral*. 2025;5(2):44. doi:10.3390/oral5020044
8. Robaian A, Alshehri AM, Alqhtani NR, et al. Effect of surface treatments and thermal aging on bond strength between veneering resin and CAD/CAM provisional materials. *Polymers*. 2025;17(5):563. doi:10.3390/polym17050563
9. Ille CE, Jivănescu A, Pop D, et al. Exploring the properties and indications of chairside CAD/CAM materials in restorative dentistry. *J Funct Biomater*. 2025;16(2):46. doi:10.3390/jfb16020046
10. Cuzic C, Rominu M, Pricop A, et al. Clinician's guide to material selection for all-ceramics in modern digital dentistry. *Materials*. 2025;18(10):2235. doi:10.3390/ma18102235
11. Chuchulska B, Dimitrova M, Vlahova A, Hristov I, Tomova Z, Kazakova R. Comparative analysis of the mechanical properties and biocompatibility between CAD/CAM and conventional polymers applied in prosthetic dentistry. *Polymers*. 2024;16(7):877. doi:10.3390/polym16070877
12. Zol SM, Alauddin MS, Said Z, et al. Description of poly (aryl-ether-ketone) materials (PAEKs), polyetheretherketone (PEEK) and polyetherketoneketone (PEKK) for application as a dental material: a materials science review. *Polymers*. 2023;15(9):2170. doi:10.3390/polym15092170
13. Moldovan F. Bone cement implantation syndrome: a rare disaster following cemented Hip Arthroplasties—Clinical considerations supported by Case studies. *J Pers Med*. 2023;13(9):1381. doi:10.3390/jpm13091381
14. de Oliveira Limírio JPJ, de Luna Gomes JM, Rezende MCRA, Lemos CAA, Rosa CDDRD, Pellizzer EP. Mechanical properties of polymethyl methacrylate as a denture base: conventional versus CAD-CAM resin–A systematic review and meta-analysis of in vitro studies. *J Prosthet Dent*. 2022;128(6):1221–1229. doi:10.1016/j.prosdent.2021.03.018
15. C Dathan P, Nair KC, S Kumar A, Lekshmy AR. Flexural strength is a critical property of dental materials-an overview. *Acta Sci Dent Scienecs*. 2023;7(7):99–103. doi:10.31080/ASDS.2023.07.1667
16. Vaidya A, Pathak K. Mechanical stability of dental materials. In: *Applications of Nanocomposite Materials in Dentistry*. Elsevier; 2019:285–305.
17. Oladapo BI, Zahedi SA, Ismail SO, Omigbodun FT. 3D printing of PEEK and its composite to increase biointerfaces as a biomedical material-A review. *Colloids Surfaces B Biointerfaces*. 2021;203:111726. doi:10.1016/j.colsurfb.2021.111726
18. Alqutaibi AY, Alghauli MA, Algabri RS, et al. Applications, modifications, and manufacturing of polyetheretherketone (PEEK) in dental implantology: a comprehensive critical review. *Int Mater Rev*. 2025;70(2):103–136. doi:10.1177/09506608251314251
19. Alqurashi H, Khurshid Z, Syed AUY, Habib SR, Rokaya D, Zafar MS. Polyetherketoneketone (PEKK): an emerging biomaterial for oral implants and dental prostheses. *J Adv Res*. 2021;28:87–95. doi:10.1016/j.jare.2020.09.004
20. Papathanasiou I, Kamposiora P, Papavasiliou G, Ferrari M. The use of PEEK in digital prosthodontics: a narrative review. *BMC Oral Health*. 2020;20(1):217. doi:10.1186/s12903-020-01202-7
21. Ramirez-Fernandez O, Duran-Gonzalez I, Equihua-Guillen F, et al. Design and structural deformation assessment of three-dimensional printed dental implants by means of finite element analysis. *Technol Heal Care*;2025. 09287329251346282. doi:10.1177/09287329251346282
22. Rezvani Ghomi E, Eshkalak SK, Singh S, Chinnappan A, Ramakrishna S, Narayan R. Fused filament printing of specialized biomedical devices: a state-of-the art review of technological feasibilities with PEEK. *Rapid Prototyp J*. 2021;27(3):592–616. doi:10.1108/RPJ-06-2020-0139
23. Mendes JM, Botelho PC, Mendes J, Barreiros P, Aroso C, Silva AS. Comparison of fracture strengths of three provisional prosthodontic CAD/CAM materials: laboratory fatigue tests. *Appl Sci*. 2021;11(20):9589. doi:10.3390/app11209589
24. Digholkar S, Madhav VNV, Palaskar J. Evaluation of the flexural strength and microhardness of provisional crown and bridge materials fabricated by different methods. *J Indian Prosthodont Soc*. 2016;16(4):328–334. doi:10.4103/0972-4052.191288
25. Kanchan LB, Majage B, Hoskhande A. Effect of thermal cycling on the marginal fit of provisional restorations fabricated using three different materials: an in vitro study. *Int J Prosthodont Restor Dent*. 2022;11(3):119–124.
26. Kiomarsi N, Saburian P, Chiniforush N, Karazifard MJ, Hashemikamangar SS. Effect of thermocycling and surface treatment on repair bond strength of composite. *J Clin Exp Dent*. 2017;9(8):e945. doi:10.4317/jced.53721
27. Liang X, Yu B, Dai Y, et al. Three-dimensional printing resin-based dental provisional crowns and bridges: recent progress in properties, applications, and perspectives. *Materials*. 2025;18(10):2202. doi:10.3390/ma18102202
28. Alharthi R, Alqahtani AR, Alshehri AM, et al. Effect of thermal aging on color stability and mechanical properties of high-density CAD/CAM polymers utilized for provisional restorations. *J Funct Biomater*. 2025;16(6):223. doi:10.3390/jfb16060223
29. Luo C, Liu Y, Peng B, et al. PEEK for oral applications: recent advances in mechanical and adhesive properties. *Polymers*. 2023;15(2):386. doi:10.3390/polym15020386
30. Limaye N, Veschini L, Coward T. Assessing biocompatibility & mechanical testing of 3D-printed PEEK versus milled PEEK. *Heliyon*. 2022;8(12):e12314. doi:10.1016/j.heliyon.2022.e12314
31. Liu Y, Yi N, Davies R, McCutchion P, Ghita O. Powder bed fusion versus material extrusion: a comparative case study on polyether-ether-ketone cranial implants. *3D Print Addit Manuf*. 2023;10(5):941–954. doi:10.1089/3dp.2021.0300
32. Hanemann T, Klein A, Baumgärtner S, Jung J, Wilhelm D, Antusch S. Material extrusion 3D printing of PEEK-based composites. *Polymers*. 2023;15(16):3412. doi:10.3390/polym15163412

33. Shrivastava SP, Dable R, Raj APN, Mutneja P, Srivastava SB, Haque M. Comparison of mechanical properties of PEEK and PMMA: an in vitro study. *J Contemp Dent Pract*. 2021;22(2):179–183. doi:10.5005/jp-journals-10024-3077
34. Muhsin SA, Hatton PV, Johnson A, Sereno N, Wood DJ. Determination of Polyetheretherketone (PEEK) mechanical properties as a denture material. *Saudi Dent J*. 2019;31(3):382–391. doi:10.1016/j.sdentj.2019.03.005
35. Rani P, Kumar S, Prakash J, J MB. Evaluation of impact strength and flexural strength of polyether ether ketone vs. computer-aided design/computer-aided manufacturing polymethyl methacrylate denture base materials: an in-vitro study. *Cureus*. 2023;15(10).
36. Barker J. *Development of a Biochemical-Thermocycling Aging Protocol for Dental Restorations*. University of Toronto (Canada); 2025.
37. Priya DJ, Lambodharan R, Balakrishnan S, Muthukumar R, Selvaraj S, Ramalingam S. Effect of aging and thermocycling on flexural strength of PEEK as a provisional restoration for full mouth rehabilitation–an in vitro study. *Indian J Dent Res*. 2023;34(1):69–74. doi:10.4103/ijdr.ijdr_195_21