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Additive Manufacturing of Dental Prosthetics: A Comprehensive Review of Accuracy, Mechanical Properties, and Clinical Feasibility

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ABSTRACT

Purpose: The present review aims to critically evaluate the dimensional accuracy, mechanical integrity, and clinical applicability of three-dimensional (3D)-printed dental prosthetics in comparison with conventional subtractive manufacturing techniques.

Materials and Methods: A systematic analysis of recent in vitro and clinical studies (2021–2026) was conducted, focusing on stereolithography (SLA), digital light processing (DLP), and selective laser melting (SLM) technologies. Parameters assessed included marginal and internal fit accuracy, flexural strength, surface hardness, and long-term aging behavior under thermocycling and water storage conditions.

Results: 3D-printed crowns demonstrated superior marginal fit (14 ± 5 µm) compared to milled counterparts (22 ± 4 µm), with statistically significant differences ($p \leq 0.022$). Nanoparticle-reinforced 3D-printed resins achieved flexural strengths ranging from 80.02 to 114.60 MPa, exceeding ISO 20795-1 requirements (65 MPa). SLA technology consistently outperformed DLP in dimensional trueness, particularly for complex multi-unit fixed partial dentures. However, 3D-printed zirconia exhibited greater variability in mechanical properties due to porosity and processing parameters, though clinically acceptable values were achieved with optimized build orientations.

Conclusion: Additive manufacturing represents a transformative paradigm in prosthetic dentistry, offering enhanced fitting precision, material efficiency, and workflow streamlining. While milled zirconia remains the benchmark for predictability, advances in resin formulations, nanoparticle reinforcement, and post-polymerization protocols position 3D printing as a viable and increasingly preferred alternative for definitive dental restorations. (*Open J Biomed Res 2026;5:34-42*)

Keywords: Additive manufacturing; dental prosthetics; dimensional accuracy; flexural strength; digital dentistry.

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AUDIOABSTRACT

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INTRODUCTION

The landscape of restorative dentistry has undergone a profound metamorphosis with the advent of computer-aided design and computer-aided manufacturing (CAD/CAM) technologies.[1] Among these innovations, additive manufacturing commonly referred to as 3D printing has emerged as a disruptive force, challenging the long-standing dominance of subtractive milling and conventional casting methods.[2] The ability to

construct complex geometries layer-by-layer from digital models offers unprecedented advantages in terms of material conservation, production speed, and customization.[3]

Contemporary 3D printing modalities employed in dental prosthodontics encompass stereolithography (SLA), digital light processing (DLP), selective laser sintering (SLS), and selective laser melting (SLM).[4] Each technology operates on distinct photopolymerization or sintering principles, yielding materials with variable mechanical and biological properties. The spectrum of printable dental materials has expanded considerably, encompassing photopolymer resins reinforced with ceramic nanoparticles, cobalt-chromium alloys, titanium, and yttria-stabilized zirconia.[5]

Despite the rapid proliferation of 3D printing in dental laboratories and clinical settings, critical questions persist regarding the long-term performance, dimensional fidelity, and biological safety of additively manufactured prosthetics.[6] The present review synthesizes contemporary evidence to elucidate the current capabilities and limitations of 3D-printed dental prosthetics, with particular emphasis on accuracy, mechanical properties, and clinical translation.

MATERIALS AND METHODS

This narrative review was structured to encompass peer-reviewed in vitro studies, systematic reviews, and meta-analyses published between 2021 and 2026. Electronic databases including PubMed, Scopus, Web of Science, and Google Scholar were interrogated using combinations of the following search terms: "3D printing," "additive manufacturing," "dental prosthetics," "CAD/CAM," "marginal fit," "flexural strength," "zirconia," and "dental resins."

Inclusion criteria encompassed studies comparing 3D-printed restorations with conventionally fabricated or milled counterparts, investigations of nanoparticle-reinforced resins, and analyses of build orientation effects on mechanical and dimensional outcomes. Studies lacking quantitative data, non-English publications, and conference abstracts without full-text availability were excluded.

RESULTS

Dimensional Accuracy and Fitting Precision

The marginal and internal adaptation of dental restorations constitutes a paramount determinant of clinical longevity. Recent comparative investigations have demonstrated that 3D-printed crowns achieve fitting discrepancies that are not merely comparable but, in several instances, superior to those of milled restorations. Crowns fabricated via additive manufacturing exhibited a mean marginal discrepancy of 14 ± 5 µm, significantly lower than the 22 ± 4 µm observed in subtractive milled crowns. Similarly, internal fit measurements favored 3D printing, with mean discrepancies of 22 ± 5 µm versus 23 ± 3 µm for milling. These comparative data are summarized in (Fig. 1), which illustrates the crown fitting accuracy differential between milling and 3D printing methodologies.

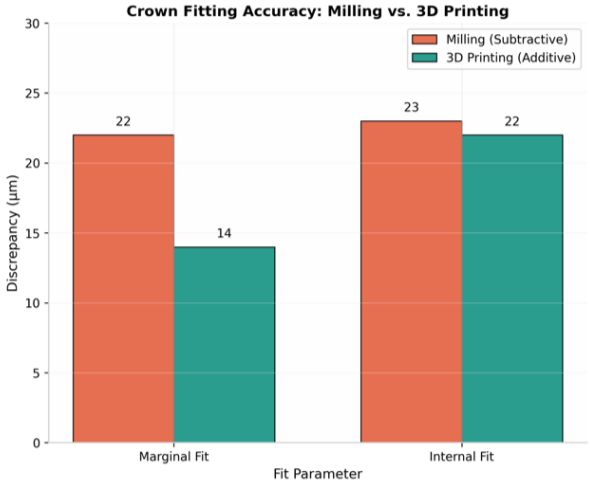


Fig 1: Comparative crown fitting accuracy between subtractive milling and additive 3D printing methodologies.

The influence of build orientation on marginal accuracy has been extensively documented. In a controlled in vitro study, crowns printed at 0° orientation demonstrated

the smallest marginal gaps (SLA: 40 ± 1.63 µm; DLP: 57 ± 1.24 µm), whereas 90° orientation yielded the largest discrepancies (SLA: 72 ± 1.2 µm; DLP: 89 ± 2.62 µm). These findings underscore the critical importance of optimizing print orientation to minimize gravitational distortion and support structure interference at the restoration margins. The relationship between build angle and marginal discrepancy is graphically represented in (Fig. 2), demonstrating the progressive deterioration in fit quality as the build orientation deviates from the horizontal plane.

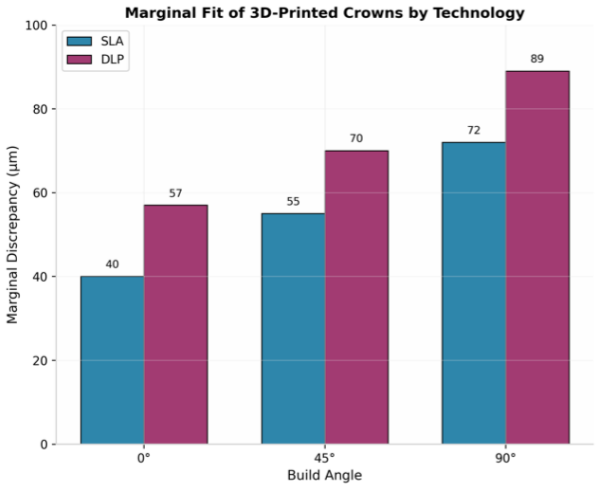


Fig. 2: Marginal fit discrepancy across SLA and DLP technologies at varying build angles (0°, 45°, 90°).

Regarding internal dimensional trueness, polymer-based fixed dental prostheses fabricated via SLA and DLP technologies achieved clinically acceptable values ranging between 17 and 52 µm. Notably, SLA consistently outperformed DLP in trueness for incisor and molar copings, attributed to the point-by-point laser polymerization mechanism that affords greater precision over the layer-by-layer projection approach of DLP. The internal dimensional trueness values across various restoration types are depicted in **(**Fig. 3**)**, highlighting the superior performance of SLA technology, particularly for complex multi-unit fixed partial dentures.

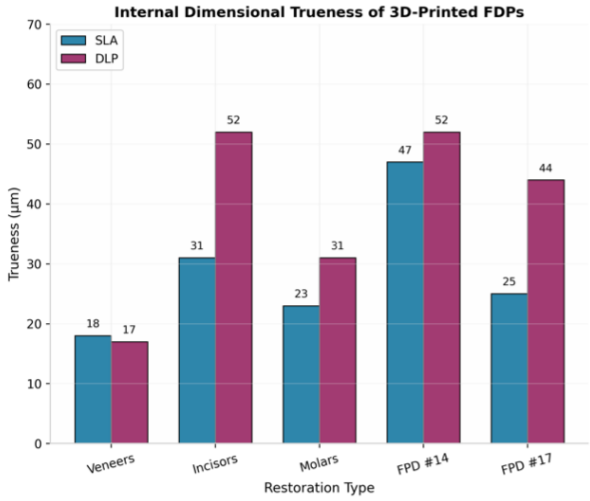


Fig. 3: Internal dimensional trueness of SLA- and DLP-fabricated fixed dental prostheses.

Mechanical Properties of 3D-Printed Resins

The mechanical robustness of 3D-printed provisional and definitive resins has been a focal point of recent research. Unmodified 3D-printed resins typically exhibit flexural strengths in the range of 79–94 MPa, which, while meeting ISO standards, fall short of conventional heat-polymerized polymethyl methacrylate and CAD/CAM block materials.

Strategic incorporation of nanoparticle fillers has emerged as a promising strategy to bridge this performance gap. An in vitro investigation demonstrated that the addition of 10% zirconia nanoparticles elevated flexural strength from 93.69 ± 5.22 MPa to 112.80 ± 9.30 MPa, while 5% and 10% glass silica reinforcement achieved 113.80 ± 11.03 MPa and 114.60 ± 4.74 MPa, respectively. Conversely, excessive filler loading (20% glass silica) precipitated a decline in flexural strength to 80.02 ± 11.35 MPa, attributable to nanoparticle agglomeration and compromised matrix homogeneity. The dose-dependent relationship between nanoparticle reinforcement and flexural strength is illustrated in (Fig. 4), with the ISO 20795-1 minimum threshold of 65 MPa indicated for comparative reference.

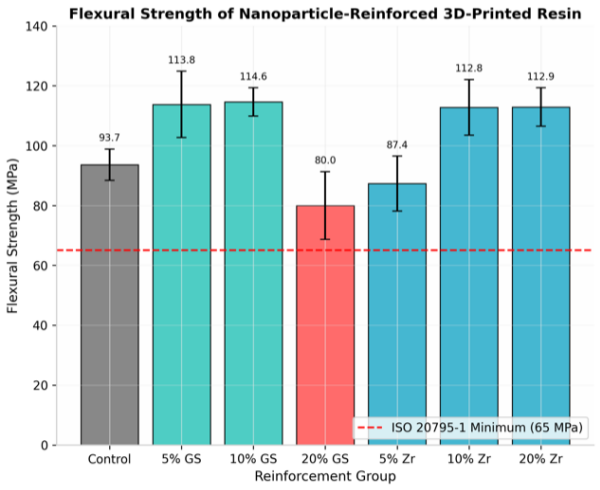


Fig. 4: Flexural strength of nanoparticle-reinforced 3D-printed resins with ISO 20795-1 minimum threshold indicated.

The long-term stability of 3D-printed restorative resins under simulated intraoral conditions has also been scrutinized. Multiple commercially available resins for permanent fixed dental prostheses were evaluated across different printer systems, subjecting specimens to water storage and thermocycling (5–55 °C, 10,000 cycles). Results indicated significant printer- and resin-dependent variations in flexural strength, Martens hardness, and elastic modulus. The 3Delta Crown resin printed with the Asiga Max system demonstrated the highest mechanical properties post-aging, highlighting the interdependence of material formulation and hardware configuration.

Comparative assessments of 3D-printed, CAD/CAM-milled, and conventional denture base materials have revealed nuanced differences in hardness and flexural properties. Polymers optimized for additive, subtractive, and conventional manufacturing exhibit distinct mechanical profiles, with wear resistance remaining comparable across modalities despite divergent hardness values.

3D-Printed Zirconia: A Meta-Analytical Perspective

Zirconia remains the material of choice for high-strength all-ceramic restorations. A recent systematic review and meta-analysis comparing CAD/CAM-milled and 3D-printed yttria-stabilized zirconia revealed no statistically significant differences in flexural strength, Vickers hardness, density, or bond strength between the two fabrication modalities. However, milled zirconia exhibited greater consistency and reliability, as reflected by higher Weibull moduli.

3D-printed zirconia demonstrated orientation-dependent mechanical behavior, with perpendicular build orientations associated with superior flexural strength. Surface treatments, including tribochemical silica coating, were found to enhance resin cement adhesion to printed zirconia, achieving bond strengths comparable to milled counterparts. These findings suggest that while 3D-printed zirconia has reached clinical viability, meticulous optimization of printing and post-processing parameters remains essential to ensure predictable performance.

The fracture toughness and hardness of 3D-printed zirconia under artificial aging conditions have been systematically evaluated, with reports indicating that printed 3Y-TZP zirconia maintains clinically relevant mechanical properties following prolonged thermocycling and water storage. Furthermore, the bond strength of milled versus printed zirconia to 10-MDP resin cement was investigated, demonstrating that ceramic conditioning protocols and disinfection procedures significantly influence adhesive durability.

A direct comparative study of flexural strength between 3D-printed and milled zirconia concluded that ceramic printing technology has advanced sufficiently to produce restorations with mechanical parity to subtractively manufactured counterparts. Additional characterization of the physiomechanical and surface properties of printed zirconia identified optimal sintering temperatures and build parameters that maximize density and minimize porosity.

Applications Across Prosthodontic Disciplines

The versatility of 3D printing extends beyond single-unit crowns to encompass complete dentures, removable partial dentures, implant surgical guides, and maxillofacial prostheses. In complete denture fabrication, SLA and DLP technologies have demonstrated favorable outcomes regarding tissue adaptation and mechanical strength, though challenges related to long-term dimensional stability and color persistence persist. For removable partial denture frameworks, SLM-fabricated cobalt-chromium alloys have shown superior fit accuracy and clasp flexibility compared to conventional cast frameworks.

Promising clinical outcomes and high patient satisfaction with 3D-printed complete dentures have been reported, noting that digital workflows reduce chairside time while maintaining acceptable functional and aesthetic parameters. These findings were further corroborated by comparative analyses of the mechanical properties of 3D-printed, CAD/CAM, and conventional denture base materials, establishing a foundational evidence base for the clinical adoption of printed prosthodontic appliances.

Emerging Materials and Interdisciplinary Applications

Beyond conventional ceramics and resins, additive manufacturing has facilitated the exploration of novel biomaterials for dental applications. Polyether ether ketone has garnered significant attention as a metal-free alternative for oral rehabilitation, with recent advances in mechanical and adhesive properties positioning it as a viable candidate for crowns, bridges, and implant abutments. Comprehensive reviews of polyether ether ketone modifications for dental use have highlighted surface treatment strategies that enhance cement adhesion and osseointegration.

The adhesion and durability of titanium–zirconia restorative materials fabricated via additive versus subtractive methods have also been investigated. Manufacturing modality significantly influences the interfacial bonding between titanium and zirconia components, with implications for the long-term stability of hybrid metal-ceramic restorations.

DISCUSSION

The integration of additive manufacturing into dental prosthodontics represents more than an incremental technological advancement it signifies a paradigm shift toward fully digital, patient-centered workflows. The evidence synthesized in this review substantiates several key assertions regarding the current state and future trajectory of 3D-printed dental prosthetics.

The consistently superior marginal fit of 3D-printed crowns, as demonstrated across multiple independent studies and visually summarized in (Fig. 1), carries profound clinical implications. Reduced marginal discrepancies translate to diminished cement layer thickness, lower risk of microleakage, and improved resistance to secondary caries and periodontal inflammation.[7] The ability to achieve marginal gaps below 50 μm well within the clinically accepted threshold of 50–150 μm positions 3D printing as a compelling alternative to milling for precision-critical applications.[8]

However, the observed variability in precision among 3D-printed restorations warrants caution. As illustrated in (Fig. 2), build orientation exerts a substantial influence on marginal accuracy, with 90° orientations producing discrepancies nearly double those of horizontal (0°) configurations.[9] The reproducibility of additive manufacturing is influenced by a constellation of factors including printer calibration, resin viscosity, ambient temperature, and post-curing protocols.[10] Standardization of these parameters across clinical and laboratory settings remains an ongoing challenge.

The mechanical performance of 3D-printed resins has been substantially enhanced through nanoparticle reinforcement strategies. The non-linear relationship between filler content and flexural strength, as depicted in (Fig. 4), highlights the complexity of composite material design.[11] While moderate filler loading improves stress distribution and crack resistance, excessive concentrations promote agglomeration and interfacial debonding, ultimately compromising structural integrity.[11] Notably, all reinforcement groups except 20% glass silica exceeded the ISO 20795-1 minimum flexural strength requirement of 65 MPa, underscoring the clinical viability of optimized formulations.

The development of ceramic-filled resins for definitive restorations represents a particularly promising avenue. Hoffmann et al. (2025) demonstrated that printer-resin interactions significantly influence mechanical outcomes, with closed-system workflows generally yielding more consistent results than open-platform configurations.[10] This finding emphasizes the need for clinician awareness regarding the specific printer-resin combinations employed in their restorations.

Wesemann et al. (2021) further illustrated that polymers designed for different manufacturing modalities conventional, subtractive, and additive possess inherently distinct mechanical profiles, necessitating material selection based on the intended fabrication method rather than universal application.[5]

The convergence of 3D printing with high-performance ceramics such as zirconia addresses one of the most persistent limitations of photopolymer resins their comparatively low fracture toughness and wear resistance.[12] The meta-analytical evidence indicates that 3D-printed zirconia can achieve mechanical parity with milled zirconia under optimized conditions, though the inherent porosity and layer-bonding artifacts of additive processes introduce greater variability.[12]

Alhotan et al. (2024) provided critical insights into the aging behavior of printed zirconia, demonstrating that fracture toughness remains stable following simulated intraoral conditions, thereby supporting the clinical viability of printed ceramic restorations.[13] Bömicke et al. (2024) complemented these findings by establishing that appropriate surface conditioning particularly tribochemical silica coating combined with 10-MDP-containing resin cement yields durable adhesive interfaces for printed zirconia comparable to those achieved with milled substrates.[14]

Future advances in ceramic suspension formulations, sintering protocols, and silane coupling agent integration are anticipated to further narrow the performance gap between printed and milled zirconia.[12,15] The potential for additive manufacturing to fabricate complex, anatomically optimized zirconia structures with minimal material waste offers a compelling sustainability advantage over subtractive methods.[16]

The application of 3D printing in removable prosthodontics has matured considerably. Herpel et al. (2021) documented high levels of patient satisfaction with 3D-printed complete dentures, attributing favorable outcomes to the precision of digital impression capture and the consistency of automated fabrication.[17] However, long-term color stability and dimensional changes under cyclic loading remain areas requiring continued investigation.[17]

Prpić et al. (2020) established that while 3D-printed denture base materials may exhibit different flexural characteristics compared to conventional heat-cured PMMA, their clinical performance remains acceptable for routine prosthodontic applications.[18] These findings collectively support the gradual transition from conventional to digital denture fabrication workflows.

The exploration of PEEK and titanium–zirconia hybrid systems represent an exciting

frontier in additive dental manufacturing. Luo et al. (2023) comprehensively reviewed surface modification strategies for PEEK, including plasma treatment, acid etching, and coating with bioactive agents, all of which enhance the material's adhesive and osteoconductive properties for dental applications.[19]

Alageel et al. (2025) investigated the durability of titanium–zirconia interfaces fabricated through additive and subtractive methods, revealing that manufacturing modality significantly influences bond strength and long-term adhesive stability.[20] These interdisciplinary advances underscore the expanding scope of 3D printing beyond traditional restorative materials toward patient-specific, biologically optimized prosthetic solutions.[21]

Despite the promising trajectory, several limitations constrain the widespread adoption of 3D-printed dental prosthetics. The long-term clinical performance data for definitive 3D-printed restorations remain limited, with most studies confined to in vitro simulations of relatively short duration. Color stability, surface degradation, and fatigue behavior under cyclic masticatory loading require further investigation.

Additionally, the biocompatibility of 3D-printed materials, while generally comparable to conventional counterparts, is contingent upon thorough post-processing to eliminate residual monomers and unreacted photoinitiators. The development of standardized biocompatibility testing protocols specific to additively manufactured dental materials represents a priority for regulatory bodies and research institutions.

CONCLUSION

Additive manufacturing has irrevocably transformed the fabrication landscape of dental prosthetics, offering demonstrable advantages in fitting accuracy, material efficiency, and workflow integration. Current evidence supports the clinical acceptability of 3D-printed crowns, FDPs, and dentures, with particular strengths in marginal adaptation and customization capability. Nanoparticle reinforcement and advanced resin formulations have substantially elevated the mechanical performance of printed polymers, while 3D-printed zirconia has achieved parity with milled ceramics under optimized conditions.

The emergence of novel biomaterials including PEEK and titanium–zirconia hybrids further expands the therapeutic possibilities of additive manufacturing in prosthodontics. Nevertheless, variability in precision, printer-resin dependency of mechanical properties, and the need for rigorous post-processing protocols necessitate continued research and standardization. As material science and printing technologies continue to evolve, additive manufacturing is poised to transition from an alternative to a preferred modality in contemporary prosthodontic practice.

Conflicts of Interest

The authors declare no conflicts of interest.

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