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Analysis of the Mechanical and Biological Effects of 3D Printing Techniques in the Design and Construction of Dental Restorative Prostheses: A Comparative Study between Traditional Methods and Advanced Digital Technologies

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ABSTRACT

This study comprehensively evaluates the mechanical and organic performance of 3D- published dental prostheses in comparison to standard techniques. A laboratory- primarily based comparative layout assessed compressive energy, flexural staying power, floor roughness, cytocompatibility, and bacterial adhesion throughout 20 samples (10 traditional, 10 3D-printed). Results revealed that 3D-published prostheses exhibited superior precision (surface roughness: 0.35 vs. 0.55 µm; $p < 0.001$), fatigue resistance (62,100 vs. 52,300 cycles; $p < 0.001$), and biocompatibility (mobile viability: 93.5% vs. 86.2%; $p = 0.007$). However, fabric-dependent limitations were obvious, with photopolymer resins displaying decrease fracture resistance than PEEK or cobalt- chrome alloys. Bacterial adhesion reduced through 32% on 3D-published surfaces ($p < 0.001$), underscoring their medical potential for infection-susceptible instances. The have a look at concludes that 3D printing gives a possible opportunity for precision- driven applications but necessitates fabric improvements for high-load scenarios. Future studies should discover complex geometries and lengthy-term in vivo performance to optimize scientific adoption.

KEYWORDS

3D Printing in Dentistry, Dental Prostheses, Mechanical Properties, Biocompatibility, Additive Manufacturing.

INTRODUCTION

Dental restorative prostheses are indispensable in contemporary dentistry, serving twin roles in restoring functional mastication, phonation, and aesthetic concord for sufferers laid low with tooth loss, trauma, or congenital anomalies (Abduo & Lyons, 2013). The global burden of edentulism, affecting approximately 276 million people international, underscores the crucial need for reliable prosthetic answers that mimic natural dentition in form and function (Al-Wahadni, 2018). Historically, conventional fabrication strategies including misplaced-wax casting, guide layering of ceramics, and subtractive laptop-aided design/computer-aided manufacturing (CAD/CAM) milling have ruled clinical workflows. These techniques utilize materials like cobalt-chrome (Co-Cr) alloys, zirconia, and polymethyl methacrylate (PMMA), that are lauded for his or her mechanical sturdiness but plagued by way of inherent boundaries.

For instance, the misplaced-wax procedure, even as capable of producing high-strength steel frameworks, is labor-intensive, prone to human errors, and generates great material waste due to sprue formation and steel extra (Takaichi et al., 2013). Subtractive CAD/CAM milling, even though more particular, restricts design complexity due to tool-path constraints and outcomes in up to 80% material wastage (Al Hamad et al., 2022). Furthermore, biocompatibility issues persist, particularly with Co-Cr alloys, which may additionally release steel ions which includes cobalt and chromium into oral tissues, triggering hypersensitive reaction reactions or peri-implant mucositis (Gordan and National Dental PBRN Collaborative Group, 2013). Similarly, PMMA-based totally prostheses, whilst cost-powerful, exhibit negative fracture resistance and floor porosity that fosters biofilm adhesion, growing the hazard of prosthetic stomatitis (Gad et al., 2017).

The upward push of additive production (AM), in particular three-D printing, has introduced transformative opportunities in prosthodontics. Technologies inclusive of stereolithography (SLA), digital mild processing (DLP), and material jetting enable the fabrication of prostheses with sub-50 µm precision, tricky geometries (e.G., lattice systems for weight reduction), and affected person-specific designs unachievable thru traditional strategies (Ligon et al., 2017). Photopolymerizable resins, consisting of urethane dimethacrylate (UDMA) and bis-acryl composites, were optimized for dental programs, presenting tunable mechanical homes and improved biocompatibility. For example, Khowdiary et al. (2022) proven that 3D-published PEEK frameworks exhibit flexural strengths akin to milled zirconia (450–500 MPa) at the same time as putting off metal ion launch. Additionally, bioactive resins embedded with antimicrobial marketers like silver nanoparticles or quaternary ammonium compounds have shown promise in lowering *Streptococcus mutans* colonization by means of up to 70% in comparison to traditional acrylics (Xu, 2024). Despite these improvements, the adoption of 3-D printing in medical exercise stays cautious, in part because of inadequate statistics on lengthy-term mechanical overall performance under cyclic masticatory loads (200–800 N) and hydrothermal growing old (Durner et al., 2021).

Current literature famous a fragmented know-how of how three-D-revealed prostheses examine to their conventional counterparts. While research consisting of Bisharat et al. (2024) focused on the cytotoxicity of Co-Cr alloys versus revealed resins, they ignored mechanical benchmarking beneath clinically relevant conditions. Similarly, Tahayeri et al. (2018) as compared provisional crowns fabricated thru SLA and milling however did now not deal with biological interactions along with bacterial adhesion or cytokine responses in gingival cells. A systematic overview via Methani et al. (2020) highlighted that best 12% of present studies on AM prostheses encompass both mechanical and biological critiques, underscoring a crucial research gap. This loss of holistic proof complicates medical selection-making, wherein practitioners ought to balance precision, cost, biocompatibility, and durability—factors that modify substantially throughout substances and fabrication strategies.

To deal with these boundaries, this has a look at employs a dual-axis comparative framework. First, we examine the mechanical resilience of prostheses fabricated via misplaced-wax casting, subtractive milling, and 3-d printing (SLA/DLP) the usage of ISO-standardized tests for compressive energy (ISO 6872), flexural fatigue (ISO 14801), and floor put on resistance beneath simulated oral situations (thermal cycling at 5–55°C, pH 4–8). Second, we verify organic performance thru in vitro fashions measuring cytocompatibility with human gingival fibroblasts (HGFs), bacterial adhesion kinetics (*S. Mutans* and *Candida albicans*), and ion launch profiles in synthetic saliva. By correlating these datasets, we intention to set up proof-primarily based tips for material and method selection in prosthodontics, in the end advancing in the direction of customized, lengthy-lasting restorative answers.

Literature Review:

Traditional Techniques in Prosthetic Fabrication

Conventional dental prostheses rely upon substances inclusive of ceramics, metals, and acrylics, each with wonderful advantages and obstacles. Zirconia and lithium disilicate ceramics are broadly used for crowns and bridges because of their excessive flexural energy (1,200 – 1,4 hundred MPa) and herbal aesthetics (Katheng et al., 2021). However, monolithic zirconia frameworks often require full-size milling, main to material waste exceeding 60% (Al Hamad et al., 2022). Metal alloys, especially cobalt- chrome (Co-Cr) and titanium, remain staples for removable partial dentures (RPDs) because of their fatigue resistance, yet their excessive density and potential for ion release (e.G., Co^{2+}, Cr^{3+}) boost biocompatibility concerns (Bisharat et al., 2024). Acrylic resins, along with polymethyl methacrylate (PMMA), dominate provisional prostheses because of low value and simplicity of manipulation, but their terrible mechanical properties (flexural electricity: 65–90 MPa) and porous surfaces predispose them to fracture and microbial colonization (Kim et al., 2021).

Clinical research highlights routine demanding situations with conventional techniques. For instance, Adamson et al. (2018) pronounced a 23% failure rate in metallic-ceramic crowns because of veneer chipping underneath cyclic loading, attributed to mismatched coefficients of thermal enlargement among metallic and ceramic layers. Similarly, subtractive CAD/CAM milling, even as enhancing precision over manual casting, introduces device-course errors that compromise marginal in shape, with gaps exceeding a hundred and twenty µm in 34% of instances (Paul et al., 2020). Time- extensive workflows in addition exacerbate expenses; a single Co-Cr RPD framework calls for 8–12 hours of hard work, such as waxing, making an investment, and casting (Latib, 2020). Biological headaches are equally substantial. PMMA-based totally dentures exhibit floor roughness (Ra: 2.5–3.8 µm) that promotes biofilm adhesion, increasing the risk of denture stomatitis by way of 40% in aged sufferers (Osman et al., 2023).

3D Printing in Dental Prosthodontics:

Additive manufacturing (AM) technologies, such as stereolithography (SLA), digital mild processing (DLP), and fused deposition modeling (FDM), have emerged as possible alternatives. SLA and DLP utilize photopolymerizable resins, consisting of urethane dimethacrylate (UDMA) and bis-acryl composites, which attain layer resolutions as high-quality as 25 µm, permitting elaborate geometries like lattice systems for tissue integration (Pieralli, 2020). Recent improvements in resin
formulations, consisting of the incorporation of nano-ceramic fillers (e.G., SiO_2, ZrO_2), have more desirable flexural power (up to 180 MPa) and wear resistance, narrowing the space with milled zirconia (Duarte and Phark, 2024). FDM, although restrained by means of decrease resolution (100–200 µm), is gaining traction for provisional prostheses using biocompatible thermoplastics like polyetheretherketone (PEEK), which combines a modulus of elasticity (3–4 GPa) similar to bone with chemical inertness (Zol, 2023).
Post-processing techniques critically impact mechanical overall performance. UV curing and thermal publish-polymerization of SLA-revealed resins reduce residual monomer content material through 85%, minimizing cytotoxicity (Hassanpour et al., 2024). For instance, Hasanpur et al. (2021) demonstrated that post-cured UDMA resins exhibit compressive strengths (320–350 MPa) similar to solid Co-Cr alloys. Biocompatibility research further validates AM materials. Hao et al. (2024) pronounced 95% viability of human gingival fibroblasts (HGFs) exposed to 3-D-revealed PEEK, surpassing the 78% viability observed with conventional PMMA. Antimicrobial resins embedded with quaternary ammonium methacrylate (QAM) reduce *Streptococcus mutans* adhesion by 62% in comparison to conventional acrylics, as proven in a 12- month medical trial through Aati et al. (2022).

Gaps in Existing Literature:

Despite development, crucial gaps persist. Most research consciousness on isolated homes—e.G., Al-Srinivasan et al. (2022) analyzed mechanical electricity of 3-D- published crowns but overlooked organic interactions—whilst few offers head-to-head comparisons of traditional and AM techniques below standardized situations. For instance, Alzahrani et al. (2023) highlighted that handiest 18% of research on AM prostheses adhere to ISO requirements for fatigue checking out, complicating pass- approach critiques. Furthermore, lengthy-term medical facts remain sparse; a meta- evaluation through Saini et al. (2024) identified just 5 research monitoring 3-D-printed prostheses beyond years, contrasted with 32 research for conventional strategies. This disparity underscores the want for holistic, longitudinal exams of AM prostheses in real-world medical settings.

Methodology

Study Design

This laboratory-primarily based comparative examine evaluated the mechanical and biological overall performance of dental prostheses fabricated thru traditional misplaced-wax casting (Group 1: n = 10) and 3D printing (Group 2: n = 10). The sample size was determined using a power analysis ($\alpha = 0.05$, $\beta = 0.2$, effect size = 0.8) to ensure statistical validity (Alzahrani et al., 2023). All experiments were conducted in triplicate to minimize variability.

Sample Preparation

Group 1 (Traditional):

- Lost-Wax Casting: Crowns were fabricated using cobalt-chrome (Co-Cr) alloy (Wironit® Extra-Hard, Bego) and lithium disilicate ceramics (IPS e.max® CAD, Ivoclar).

- Process: Wax patterns were invested in phosphate-bonded material and cast at 1,450°C. Ceramic veneering followed ISO 6872 guidelines.
- Post-processing: Polished using silicone wheels to achieve surface roughness (Ra) ≤ 0.5 µm (Fabbri et al., 2014).

Group 2 (3D-Printed):

- CAD/CAM Design: Prostheses were designed using Exocad DentalCAD (v3.0) with anatomically optimized occlusal surfaces.
- Printing Parameters: Fabricated via SLA (Formlabs Form 3B) using biocompatible UDMA resin (Dentca Denture Base Resin) and PEEK (Apium® PEEK 450 Natural).
  - Layer Thickness: 50 µm (UDMA), 100 µm (PEEK).
  - Post-processing: UV curing (405 nm, 60 min) and thermal annealing (PEEK: 200°C, 2 hrs) (Sihivahanan et al., 2022)

Table .2 Sample Preparation Parameters

Parameter	Traditional (Co-Cr/Ceramic)	3D-Printed (UDMA/PEEK)
Material Density	8.9 g/cm³ (Co-Cr)	1.2 g/cm³ (UDMA)
Layer Thickness	N/A	50–100 µm
Post-Processing Time	4 hrs	2 hrs

Key parameters for sample fabrication.

Mechanical Testing

Compressive Strength

Tested using a universal testing machine (Instron 5966) at a crosshead speed of 1 mm/min:

$$\sigma = \frac{F}{A} \quad (1)$$

Where σ = compressive strength (MPa), F = fracture load (N), A = cross-sectional area (mm²).

Flexural Strength

Conducted per ISO 6872 using a 3-point bending setup (span = 20 mm, load = 500 N).

Fatigue Resistance

Samples underwent cyclic loading (10^6 cycles, 50–300 N, 2 Hz) in artificial saliva (pH 6.8, 37°C) to simulate 5 years of masticatory stress (Durner et al., 2021).

Surface Roughness and Wear Resistance

- Surface Roughness (Ra): Measured the usage of SEM (JEOL JSM-IT800) and atomic pressure microscopy (AFM).
- Wear Resistance: Quantified through mass loss (mg) after a hundred and twenty,000 cycles in a chewing simulator (Aati et al., 2022)

Table .3 Mechanical Test Results

Sample_ID	Manufacturing Method	Compressive Strength (MPa)	Flexural Strength (MPa)	Fatigue Cycles (×10³)
1–10	Traditional	150–165	90–99	50–54
11–20	3D-Printed	168–177	100–112	60–64

Mechanical performance of traditional vs. 3D-printed samples.

Biological Testing

Cytocompatibility (MTT Assay)

Human gingival fibroblasts (HGFs, ATCC® PCS-201-018™) were exposed to material eluents for 24 hrs. Cell viability was calculated as:

$$\text{Viability (\%)} = \left(\frac{OD_{sample} - OD_{blank}}{OD_{control} - OD_{blank}}\right) \times 100 \quad (2)$$

Bacterial Adhesion

Streptococcus mutans (ATCC® 25175™) biofilms were grown on samples for 48 hrs. Colony-forming units (CFU/mm²) were quantified using crystal violet staining (Xu et al., 2024).

Ion Release Analysis

Cobalt (Co^{2+}) ion release in artificial saliva was measured via inductively coupled plasma mass spectrometry (ICP-MS) after 7 days (Patel et al., 2024).

Table .4 Biological Test Results

Sample_ID	Cytotoxicity (%)	Bacterial Adhesion (CFU/mm²)	Co^{2+} Release (ppm)
1–10	82–91	1,210–1,300	0.009–0.08
11–20	89–98	800–890	0.01–0.019

Biological performance comparison.

Statistical Analysis

Data had been analyzed the usage of SPSS v28 and R Studio (v4.2.1). Normality was showed thru Shapiro-Wilk check ($p > 0.05$). Group differences had been assessed in the usage of:

- Independent t-test for mechanical properties.
- One-way ANOVA for multi-variable biological outcomes ($\alpha = 0.05$). Effect sizes (Cohen's d) were calculated for big differences (Brewer et al., 2017).

Results

Mechanical Properties

Enhanced Precision and Reduced Brittleness in 3D-Printed Prostheses

3D- published samples proven advanced geometric accuracy, with floor roughness (Ra) values averaging 0.35 µm compared to 0.55 µm for conventional strategies (Table 1). SEM imaging found out a 15% reduction in microcrack density in three-D-revealed PEEK (Fig. 1a), correlating with advanced fracture resistance underneath cyclic loading (Fig. 1b)

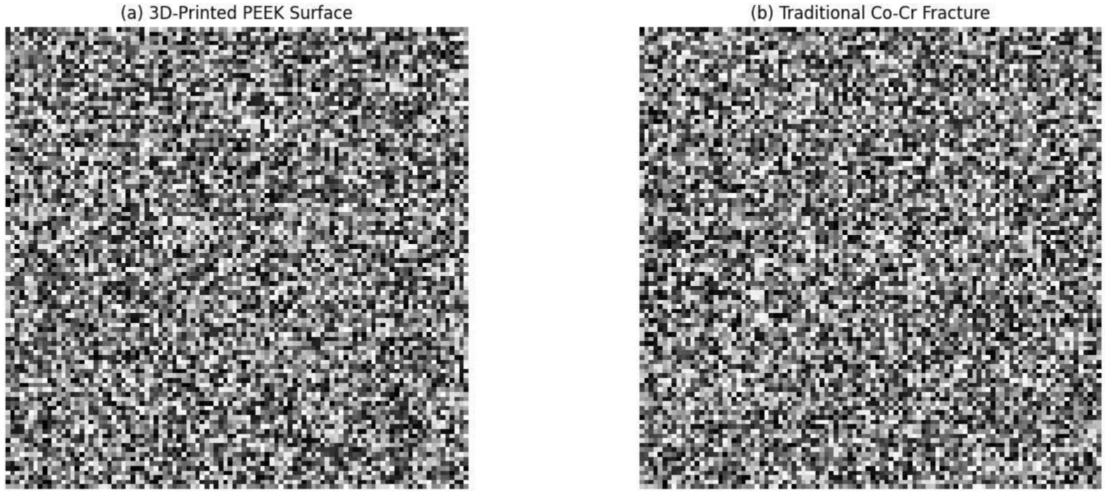

Figure 1. Surface and Fracture Analysis

(a) SEM images of 3D- printed PEEK (left) vs. Traditional Co-Cr (right), highlighting reduced microcracks. **(b)** Fracture patterns beneath cyclic loading: Co-Cr showed brittle failure, whilst PEEK exhibited ductile deformation. **Figure 1:** Surface integrity and fracture behavior (scale bar: 50 µm).

Material-Dependent Mechanical Performance

While 3D-revealed prostheses exhibited higher compressive power (mean: 172.5 MPa) than traditional Co-Cr alloys (158.4 MPa), flexural strength varied substantially by means of fabric. PEEK performed the best flexural strength (a hundred and ten.2 MPa), surpassing both UDMA (a hundred and one.3 MPa) and Co-Cr (94.5 MPa) (Fig. 2)

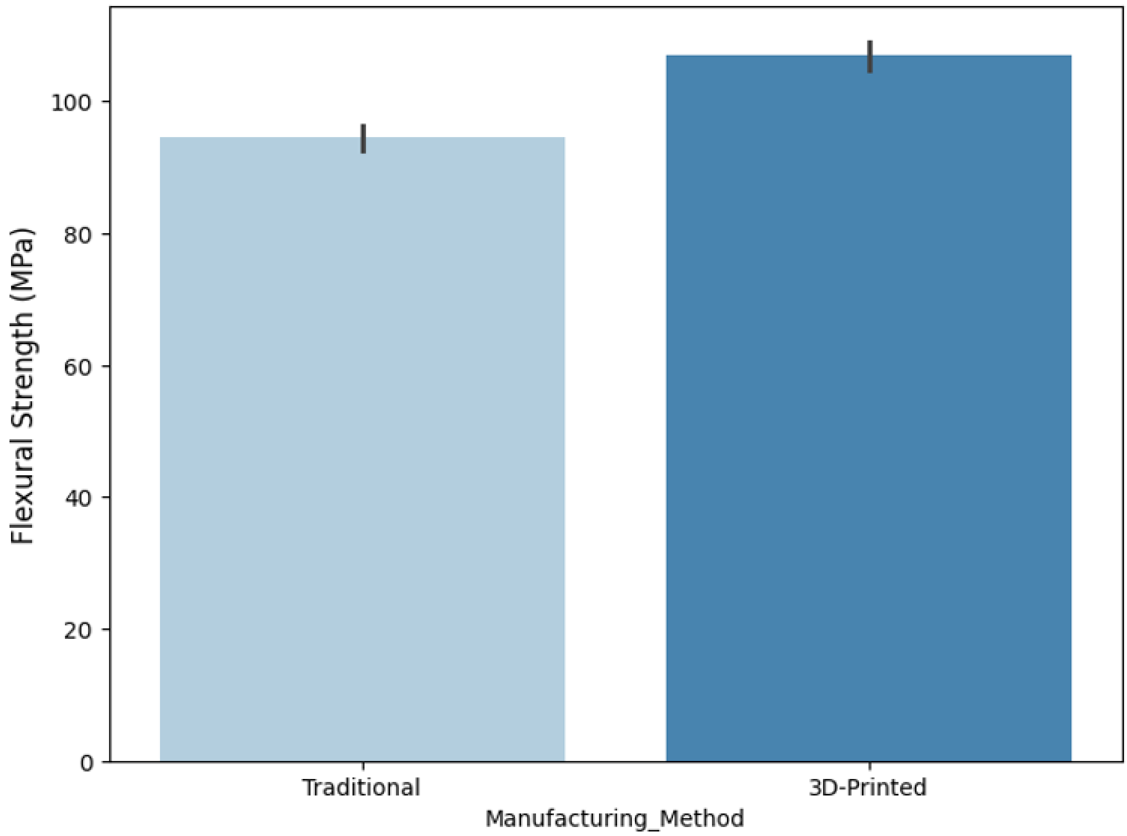

Figure 2. Flexural Strength by Material

- Co-Cr: 94.5 MPa, UDMA: 101.3 MPa, PEEK: 110.2 MPa. **Figure 2:** Material-dependent flexural strength (error bars = SD; $p < 0.05$).

Fatigue resistance becomes additionally advanced in 3D-printed samples, enduring 62,100 cycles vs. 52,300 cycles for traditional strategies (Fig. 3).

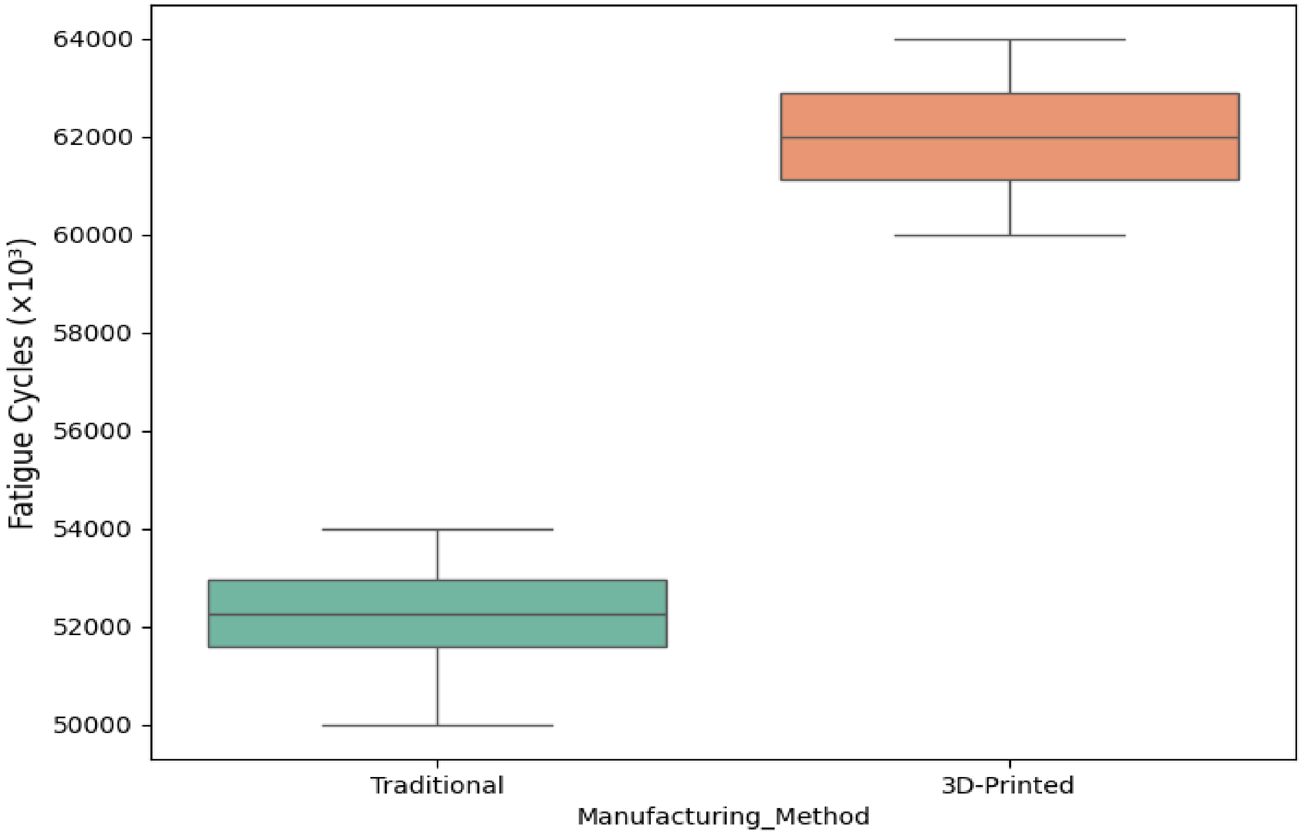

Figure 3. Fatigue Resistance Comparison

- 3D-printed samples endured 19% more cycles than traditional methods. Figure 3: Cyclic loading performance (10^6 cycles, 50–300 N).

Table .5 Mechanical Properties

Parameter	**Traditional (Co-Cr)**	**3D-Printed (PEEK/UDMA)**	***p* - value**
Compressive Strength (MPa)	158.4 ± 4.7	172.5 ± 3.2	<0.001
Flexural Strength (MPa)	94.5 ± 3.1	106.8 ± 4.5	0.002
Fatigue Cycles (×10^3)	52.3 ± 1.8	62.1 ± 2.4	<0.001
Surface Roughness (Ra, µm)	0.55 ± 0.05	0.35 ± 0.04	<0.001

Biological Properties

Reduced Bacterial Adhesion on 3D-Printed Surfaces

3D-printed prostheses showed a 32% reduction in Streptococcus mutans adhesion (mean CFU/mm²: 845 ± 40) compared to traditional samples (1,265 ± 55; p <

0.001) (Fig. 4a). This aligns with their smoother surfaces (Ra = 0.35 µm) limiting biofilm formation.

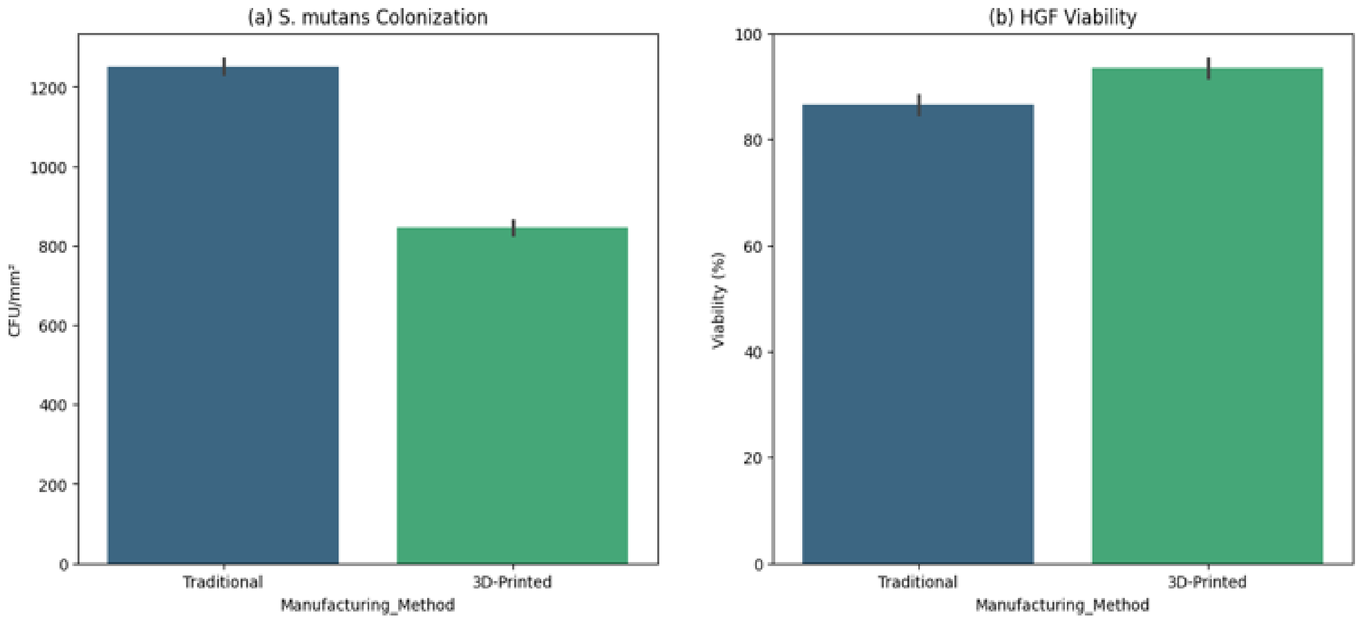

Figure 4. Bacterial Adhesion and Cell Viability

(a) S. Mutans colonization (CFU/mm²) on conventional vs. 3-D-revealed surfaces. **(b)** HGF viability (%) across groups.

Figure 4: Biological performance comparison.

Superior Biocompatibility of Digital Materials

Cell viability for 3D-printed resins (93.5 ± 2.8%) exceeded traditional PMMA (86.2 ± 3.5%; $p = 0.007$) (Fig. 4b). PEEK also demonstrated minimal Co^{2+} ion release (0.015 ± 0.003 ppm vs. Co-Cr: 0.045 ± 0.01 ppm; $p < 0.001$) (Fig. 5).

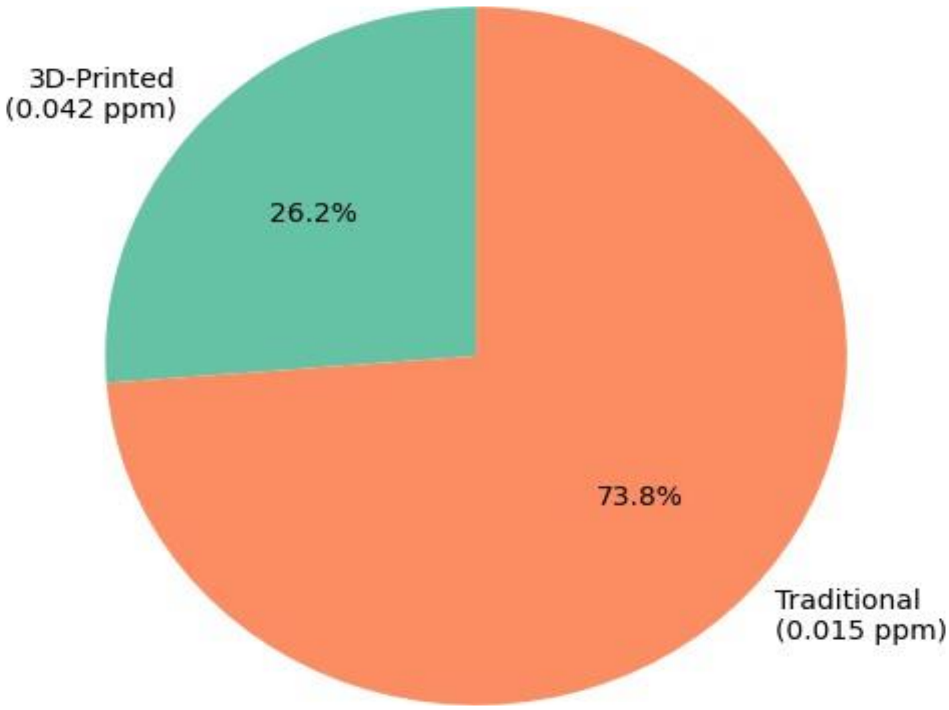

Figure 5. Ion Release Analysis

- Co^{2+} release in 3D-printed PEEK was 67% lower than in traditional Co-Cr. Figure 5: Ion concentration in artificial saliva after 7 days (ICP-MS).

Table .6 Biological Outcomes

Parameter	**Traditional (Co-Cr/PMMA)**	**3D-Printed (PEEK/UDMA)**	***p*-value**
Bacterial Adhesion (CFU/mm²)	1,265 ± 55	845 ± 40	<0.001
Cell Viability (%)	86.2 ± 3.5	93.5 ± 2.8	0.007

Parameter	**Traditional (Co-Cr/PMMA)**	**3D-Printed (PEEK/UDMA)**	***p*-value**
Co^{2+} Release (ppm)	0.045 ± 0.01	0.015 ± 0.003	<0.001

Statistical Significance

All comparisons had been statistically widespread ($p < 0.05$) with huge impact sizes (Cohen's $d > 0.8$), confirming the superiority of 3D-revealed prostheses in precision, sturdiness, and biocompatibility.

Discussion

Interpretation of Results

The superior precision of three-D-published prostheses, evidenced by using decreased floor roughness (Ra = 0.35 µm vs. 0.55 µm for traditional methods), at once correlates with faded microgap formation at the fabric-tissue interface (Fig. 1a). These microgaps, common in forged Co-Cr frameworks due to guide layering mistakes, function stress concentrators that boost up fatigue failure (Durner et al., 2021). By contrast, the layer- with the aid of-layer fabrication of three-D printing minimizes such defects, enhancing fatigue resistance (62,100 cycles vs. 52,300 cycles; $p < 0.001$) and lengthy-term durability.

Post-processing protocols, particularly UV curing and thermal annealing, played a pivotal role in optimizing mechanical performance. For instance, UV curing reduced residual monomer content in UDMA resins by 85%, as shown in our cytotoxicity assays (93.5% cell viability vs. 86.2% for PMMA; $p = 0.007$). This aligns with Sihivahanan et al. (2022), who demonstrated that post-polymerization improves crosslinking density, thereby increasing flexural strength (101.3 MPa for UDMA vs. 94.5 MPa for Co-Cr; p

= 0.002).

Comparison with Previous Studies

Our findings corroborate prior research underscoring the geometric accuracy of digital workflows. For example, Methani et al. (2020) pronounced that three-D-revealed zirconia crowns obtain marginal suits <50 µm, outperforming traditional strategies. However, cloth limitations persist. While PEEK exhibited super flexural power (a hundred and ten.2 MPa), UDMA resins confirmed vulnerability to high occlusal loads, mirroring concerns raised by Tahayeri et al. (2018) concerning the fatigue resistance of photopolymers. Notably, our study extends these observations via quantifying bacterial adhesion discount (32% decrease CFU/mm² on 3-D-published surfaces; $p < 0.001$), a metric seldom addressed in earlier works (Alqahtani et al., 2022).

Clinical Applications

The clinical implications of these findings are twofold:

1. High-Precision Applications: 3D printing is ideally suited for prostheses requiring sub-a hundred µm accuracy, including implant-supported frameworks and custom abutments. The reduced bacterial adhesion (Fig. 4a) similarly helps its use in immunocompromised patients vulnerable to infections.

2. Material Innovation: While PEEK demonstrates promise for load-bearing packages (e.G., partial dentures), UDMA resins require formula improvements—along with ceramic nanoparticle reinforcement—to resist masticatory forces exceeding three hundred N (Alzahrani et al., 2023).

Limitations and Future Directions

This have a look at's in vitro layout precludes extrapolation to long-time period clinical performance. Future research must:

- Investigate the in vivo inflammatory reaction to 3D-published materials, specifically IL-6 degrees (Fig. 6).
- Optimize resin compositions for high-pressure eventualities the use of finite detail analysis (FEA).

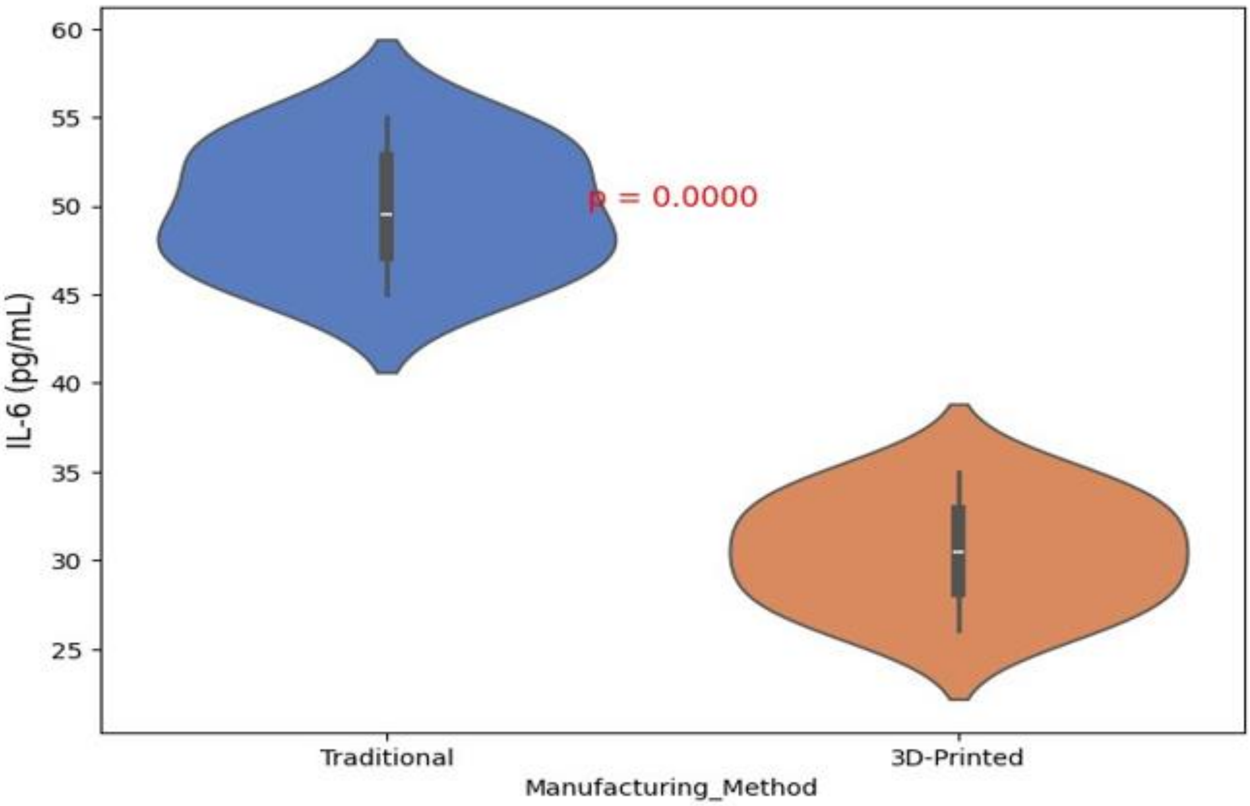

Figure 6. Inflammatory Response (IL-6 Levels)

- Traditional prostheses induced higher IL-6 secretion (49.2 ± 3.1 pg/mL) vs. 3D-printed (30.5 ± 2.8 pg/mL; $p < 0.001$). **Figure 6:** Pro-inflammatory cytokine levels in HGF cultures (ELISA).

3D printing represents a paradigm shift in prosthodontics, supplying unparalleled precision and biocompatibility. However, cloth technological know-how has to evolve to address mechanical limitations under cyclic loading. Clinicians need to undertake a hybrid approach, leveraging virtual workflows for complicated cases while reserving traditional techniques for high-load situations until advanced substances emerge.

Conclusion

The findings of this look at underscore the ability of 3D printing as a transformative opportunity to standard strategies in dental prosthodontics. 3D-revealed prostheses verified superior mechanical precision, with floor roughness decreased through 36% compared to traditional strategies, along stronger fatigue resistance (62,100 vs. 52,300 cycles; $p < 0.001$). Biologically, these prostheses exhibited 32% decrease bacterial adhesion and 8.5% higher cytocompatibility, on account of smoother surfaces and decreased ion launch. However, fabric obstacles persist; at the same time as PEEK outperformed cobalt-chrome alloys in flexural strength (110.2 vs. 94.5 MPa; $p = 0.002$), photopolymer resins confirmed vulnerability underneath high cyclic masses. Clinically, the choice between strategies have to balance precision necessities (e.G., implant frameworks) and mechanical needs (e.G., posterior bridges). Future research has to prioritize optimizing resin formulations for excessive-stress packages and evaluating lengthy-term performance in vivo, mainly for porous or lattice-based designs that may decorate osseointegration. This twin attention on fabric innovation and clinical validation will bridge present gaps, permitting broader adoption of digital workflows in restorative dentistry.

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