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Digital Dentistry in Prosthodontics: Evaluating the Accuracy of 3D Printed Implant-Supported Prostheses.

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Abstract

Background: The use of 3-dimensional (3D) printing has grown to be a part and parcel of digital dentistry, but concerns remain about the accuracy of the implant-supported prostheses produced by additive manufacturing. ***Objective:*** To evaluate the accuracy of 3D-printed implant-supported prostheses and compare their marginal adaptation and dimensional accuracy with CAD/CAM milled prostheses. ***Methods:*** This was an in vitro, analytical cross-sectional study, which involved 66 implant-supported prostheses, half of which were 3D-printed, and the other half CAD/CAM milled. The following discrepancies were measured with the aid of digital stereomicroscopy and three-dimensional inspection software: marginal discrepancy, internal fit, root mean square (RMS) deviation, vertical misfit, and horizontal misfit. Independent t-test, Chi-square test, Pearson correlation, and multiple linear regression were used to analyze data with a significance level $p<0.05$. ***Results:*** CAD/CAM milled prostheses demonstrated significantly lower marginal discrepancy (46.2 ± 6.9 vs. 54.8 ± 8.6 µm), improved internal fit (74.4 ± 8.2 vs. 83.6 ± 10.5 µm), and lower RMS deviation (31.9 ± 4.9 vs. 38.4 ± 5.8 µm) than 3D-printed prostheses (all $p<0.001$). The 100% passively fit, and 90.9% of the 3D-printed prostheses were clinically acceptable. The printing time and RMS deviation were significant factors affecting the marginal discrepancy. ***Conclusion:*** CAD/CAM milling showed clearly improved dimensional accuracy, while implant-supported prostheses created by 3D printing showed clinically acceptable adaptation and can be considered a reliable and efficient alternative in the field of digital prosthodontic rehabilitation.

Keywords: Digital dentistry, 3D printing, Implant-supported prosthesis, CAD/CAM, Marginal discrepancy.

INTRODUCTION

The incorporation of digital technologies into prosthodontics has revolutionized traditional clinical workflows, making them more precise, efficient, and patient-centered.[1] Digital Dentistry refers to the use of computer-aided design/computer-aided manufacturing (CAD/CAM), intraoral scanners, cone-beam computed tomography (CBCT), and additive manufacturing (3D printing) for dental diagnosis, planning, fabrication, and delivery of dental prostheses.[2] One of those innovations is 3D printing, which has given a much-needed boost to implant prosthodontics by creating highly customized implant supported prostheses that use less material, take less time to produce, and are easier to reproduce.[3] The accuracy of digitally fabricated restorations has become a key factor in the long-term clinical success of implant-supported restorations, which are in growing demand around the world.[4]

The high success rate of dental implants and the satisfactory functional and esthetic results have made it the treatment of choice for the replacement of missing teeth.[5] Current epidemiological data show that more than 12 million dental implants are inserted worldwide every year and that these numbers grow by around 500,000 to 1 million annually due to the aging of the population and the growing knowledge of implant dentistry.[6] Moreover, the global dental implant market was worth over USD 5 billion in recent years and is expected to register a CAGR of more than 7% during the forecast period, owing to technological advancements and growing patient demand for esthetic rehabilitation, coupled with the high prevalence of edentulism.[7] As such, digital workflows have been implemented in parallel to enhance the efficiency of treatment and the accuracy of the prosthetics.[8]

The advent of Additive Manufacturing has transformed the manufacturing of implant-supported prostheses, allowing for their production in layers based on digital design.[9] 3D printing has several advantages over subtractive manufacturing, including lower manufacturing costs, less material waste, quick turnaround, and the ability to create complex shapes that would be hard to achieve through traditional manufacturing processes.[10] The most popular 3D printing approaches used in dentistry today are stereolithography (SLA), digital light processing (DLP), selective laser melting (SLM), and fused deposition modeling (FDM), and each is utilized to produce a wide range of dental products, such as implant models, complete dentures, provisional restorations, and surgical guides.[11] The clinical uses of 3-D printing in restorative dentistry have also grown with the development of new materials that can be printed, such as ceramics, metal alloys, and resins.[12]

The growing popularity of digital dentistry and the increasing use of additive manufacturing in everyday prosthetic treatment require more evidence to assess the accuracy of 3D-printed implant-supported prostheses under standardized clinical conditions. This evidence will guide the clinician in selecting relevant digital workflows and in optimizing clinical treatment results and minimizing complications associated with prostheses. The objective of the present study was to assess the accuracy of 3D-printed prostheses supported by implants based on key parameters of the prosthetic fit and adaptation and to evaluate the clinical suitability for implant rehabilitation.

METHODOLOGY

The aim of this analytical cross-sectional in vitro study was to assess the accuracy of 3D-printed implant-supported prostheses made with the fully digital approach. The study involved comparing the marginal and internal fit of implant-supported prostheses fabricated using a standardized digital design and fabrication approach by three-dimensional (3D) printing technology. The study was carried out in the Department of Prosthodontics. Standardized laboratory equipment was used in a controlled environment to minimize measurement variability and to perform these activities, such as digital designing, additive manufacturing, post-processing, and accuracy assessment. The study was conducted over a period of six months, from July to December, 2025.

A sample size for comparison of two independent means was calculated with the OpenEpi Version 3.01 sample size calculator. The calculation was done based on the study carried out by Donmez and Okutan (2022), which was aimed at the evaluation of the marginal gap of implant-supported 3D-printed and CAD/CAM milled crowns. The mean baseline values of the marginal gaps reported in the study were around 47.0 ± 8.0 µm for the 3D-printed group and 56.0 ± 10.0 µm for the milled group.[13] With a 95% confidence level, 80% study power, and an equal allocation ratio (1:1), the minimum sample size required was 20 specimens per group (40 implant-supported prostheses). To account for possible measurement errors or printing defects, 10% of the original sample size was added, resulting in a total sample size of 44 prostheses (22 in each group).

A non-probability consecutive sampling technique was used. Every implant-supported prosthesis made throughout the study period that met the predetermined inclusion criteria was added to the sample until the required number of prostheses was obtained. The study comprised implant-supported prostheses made with standardized CAD software and identical implant systems. Prostheses were created with the same digital workflow and were printed with a calibrated 3D printer with the same printing parameters. Prostheses that were printed with different resin or metal material or had fabrication defects were excluded from the analysis. Printing failures, incomplete polymerization, visible fractures, distortion, surface defects, and post-processing damage were not permitted. Prostheses requiring remanufacturing due to software or hardware errors were also excluded. Samples that were not completely digitized or that were not positioned correctly during the preparation of the model were not part of the final analysis.

After IRB approval, a standard master implant model with two parallel implant analogs was created. A calibrated intraoral scanner was used to take digital impressions of the master model, and all the prostheses were designed with computer-aided design (CAD) software with the same design specifications. Digital designs were exported as Standard Tessellation Language (STL) and printed with a high-resolution stereolithography (SLA) 3D printer with standardized printing parameters, such as layer thickness, build orientation, exposure time,, and support structure.

All prostheses were then cleaned, post-cured, and finished in a standard fashion per the manufacturer's recommendations after they were fabricated. Afterwards, each prosthesis was positioned on the master implant model with the recommended implant tightening torque. The marginal discrepancy and internal fit were assessed at predetermined locations around each implant interface by means of a digital stereomicroscope and image analysis software. To reduce the measurement error, three independent measurements were taken at each location, and an average value was taken for statistical analysis. The dimensional accuracy (trueness) was determined by overlaying the STL models of the printed prostheses with the 3D reference CAD model using three-dimensional inspection software and calculating the root mean square (RMS) deviation.

The two calibrated examiners were blinded to the fabrication sequence and performed all measurements. Demographic laboratory variables, which included printing time, post-processing time, marginal discrepancy (µm), internal fit (µm), RMS deviation (µm), and presence of clinically acceptable passive fit, were documented on a structured data collection proforma.

The data collected were entered and analyzed in IBM Statistical Package for Social Sciences (SPSS) version 27.0. Data on continuous variables (marginal discrepancy, internal fit, RMS deviation, printing time, and post-processing time) were expressed as mean ± standard deviation, and categorical variables were expressed as frequency and percentage. The Shapiro–Wilk test was used to check for normality of the data. The independent samples t-test was used to compare variables between groups for normally distributed variables. The relationship between categorical variables was analyzed by the Chi-square test and Fisher's exact test. The intraclass correlation coefficient (ICC) was used to measure inter-examiner reliability. A two-tailed p-value of <0.05 was considered statistically significant.

RESULTS

A total of 66 implant-supported prostheses were analysed across the two groups: 33 were 3D printed, and 33 were CAD/CAM milled prostheses. The 3D-printed group was found to have a significantly shorter fabrication time than the CAD/CAM milled group (48.6 ± 5.2 minutes vs. 72.9 ± 6.8 minutes, respectively, p<0.001), but significantly longer post-processing times (18.7 ± 2.4 minutes vs. 10.5 ± 1.8 minutes, respectively, p<0.001). There was no difference in the frequency of fabrication defects (p=0.554) or thickness of the prosthesis (p=0.431) between the groups. (Table 1)

Table 1. Baseline Fabrication Characteristics of Implant-Supported Prostheses (n = 66)

Variable	3D Printed (n=33) n(%)/Mean±SD	CAD/CAM Milled (n=33) n(%)/Mean±SD	P-value
Printing/Milling time (minutes)	48.6 ± 5.2	72.9 ± 6.8	<0.001*
Post-processing time (minutes)	18.7 ± 2.4	10.5 ± 1.8	<0.001*
Prosthesis thickness (mm)	1.51 ± 0.04	1.50 ± 0.05	0.431
Number of supports removed	18.4 ± 2.8	—	—
Fabrication defects	2 (6.1)	1 (3.0)	0.554†

*Independent Samples t-test
†Fisher's Exact Test

The accuracy of the prostheses proved to be significantly superior for CAD/CAM milled prostheses than for 3D printed prostheses when compared to accuracy. Conventionally milled prostheses showed significantly higher dimensional accuracy and adaptation by being significantly lower in marginal discrepancy, internal fit, root mean square (RMS) deviation, vertical misfit, and horizontal misfit compared to the 3D-printed prostheses (all p<0.001). However, the values recorded for both groups were still clinically acceptable. (Table 2)

Table 2. Comparison of Accuracy Parameters Between Study Groups

Variable	3D Printed (n=33) Mean ± SD	CAD/CAM Milled (n=33) Mean ± SD	P-value
Marginal discrepancy (µm)	54.8 ± 8.6	46.2 ± 6.9	<0.001*
Internal fit (µm)	83.6 ± 10.5	74.4 ± 8.2	<0.001*
RMS deviation (µm)	38.4 ± 5.8	31.9 ± 4.9	<0.001*
Vertical misfit (µm)	41.7 ± 6.2	35.1 ± 5.5	<0.001*
Horizontal misfit (µm)	35.8 ± 5.3	29.8 ± 4.7	<0.001*

*Statistically significant (p<0.05)

The clinical acceptability assessment demonstrated that all CAD/CAM milled prostheses had an acceptable passive fit, while 90.9% of the 3D-printed prostheses matched the set clinical criteria. A small number of 3D-printed prostheses showed a slight deviation above the acceptable limit, but the difference between the two methods of production was not statistically significant (p=0.076). (Table 3)

Table 3. Clinically Acceptable Prosthetic Fit According to Study Groups

Variable	3D Printed n (%)	CAD/CAM Milled n (%)	χ^2	P-value
Acceptable fit (<120 µm)	30 (90.9)	33 (100.0)	3.14	0.076
Not acceptable (≥120 µm)	3 (9.1)	0 (0.0)		

*Chi-square Test

In the 3D-printed group, moderate positive correlations were observed between fabrication time and marginal discrepancy (r=0.46, p=0.007), internal fit (r=0.39, p=0.024), and RMS deviation (r=0.42, p=0.015). The results indicate that the longer the print time, the higher the dimensional inaccuracy slightly. (Table 4)

Table 4. Correlation Between Printing Time and Accuracy Parameters in the 3D Printed Group (n=33)

Variable	Pearson's r	P-value
Printing time vs Marginal discrepancy	0.46	0.007*
Printing time vs. internal fit	0.39	0.024*
Printing time vs RMS deviation	0.42	0.015*
*Pearson Correlation		

RMS deviation and fabrication time were found to be a set of independent predictors for the marginal discrepancy using multiple linear regression analysis. The largest positive correlation was found for RMS deviation (β=0.51, p<0.001), followed by fabrication time (β=0.42, p<0.001) and post-processing time (p=0.195), which did not significantly affect the marginal accuracy. The regression model accounted for 56% of the variation in the marginal discrepancy (Adjusted R^2=0.53, p<0.001). (Table 5)

Table 5. Predictors of Marginal Discrepancy (Multiple Linear Regression)

Variable	β Coefficient	Standard Error	Standardized β	t	P-value
Printing time	0.38	0.09	0.42	4.18	<0.001*
Post-processing time	-0.15	0.12	-0.14	-1.31	0.195
RMS deviation	0.47	0.10	0.51	4.69	<0.001*
Constant	11.84	5.63	—	2.10	0.040
Model statistics: **R^2 = 0.56; Adjusted R^2 = 0.53; F = 25.4; p < 0.001**					

There was excellent agreement for all accuracy measurements as established by inter-examiner reliability analysis. The intraclass correlation coefficients were between 0.951 and 0.969, which indicates good reproducibility and consistency of the measurement procedure used in this study. (Table 6)

Table 6. Inter-Examiner Reliability for Accuracy Measurements

Measurement	Intraclass Correlation Coefficient (ICC)	95% CI
Marginal discrepancy	0.964	0.932-0.981
Internal fit	0.951	0.915-0.974
RMS deviation	0.969	0.941-0.984
Vertical misfit	0.958	0.924-0.978
Horizontal misfit	0.962	0.930-0.980

DISCUSSION

The present study aimed to assess the accuracy of 3D-printed implant-supported prostheses by comparing the marginal discrepancy, the internal fit, the dimensional accuracy, and the passive fit with the CAD/CAM milled prostheses. The CAD/CAM group showed significantly better marginal adaptation, internal fit, and RMS deviation values compared to the 3D-printed group, but the values of these parameters for the 3D-printed prostheses were clinically acceptable. The results show that although the accuracy of the additive manufacturing technique was slightly higher than that of subtractive manufacturing, it is clinically acceptable for implant-supported restorations.

The present study revealed that the marginal discrepancy of CAD/CAM milled prostheses was significantly lower than that of 3D printed prostheses. The results of this study are also in line with the systematically performed review and meta-analysis conducted by a study who found that both the additive and the subtractive manufacturing processes resulted in clinically acceptable marginal fit; however, the precision of the 3D-printed restorations was comparable to the precision of the milled restorations in the case of implant-retained fixed partial dentures (FPDs), but milled restorations were more precise for complete-arch FPDs.[14]

Likewise, our results support the systematic review conducted by Ellakany et al. (2025), who analysed over 100 studies and found acceptable implant-supported prostheses were obtained in both digital manufacturing workflows. The results showed that milled restorations exhibited consistently high dimensional accuracy, flexural strength, and fracture resistance, while 3D printing yielded some benefits in manufacturing efficiency and marginal adaptation.[15] The present observations are in line with the above-mentioned results, which showed that the milled prostheses yielded a better fit compared to 3D-printed prostheses, which were clinically acceptable.

The mean marginal discrepancy of the 3D-printed group in the present study was within the standard clinical limit of 120 µm. The result is in line with the systematic review of Rutkūnas et al. (2022), who found that the tolerance, or tolerances, of the implant-supported prostheses produced by additive manufacturing generally ranged from about 23 µm to more than 200 µm, with most studies showing a clinically acceptable adaptation similar to conventional manufacturing methods.[16]

The results of Hwang et al. (2022), which observed that different digital workflows affect the trueness of the implant-supported restorations, also support the higher internal fit and RMS deviation recorded for the 3D-printed prostheses. Their study found that the cast-free digital workflow resulted in higher intaglio surface trueness than the workflow that involved the 3D printing of casts, highlighting that each extra manufacturing stage can add dimensional error.[17]

The present study showed that over 90% of the 3D-printed prostheses had clinically acceptable passive fit when compared to CAD/CAM restorations, despite higher discrepancies. Similar results were reported by He et al. (2026) in a systematic review, which found that the majority of 3-unit implant-supported 3D-printed cobalt-chromium prostheses had clinically acceptable marginal fit. In the case of long-span complete-arch prostheses, however, most of the findings agree with the superior adaptation of milled frameworks, as reported in this study.[18]

The other significant result of the present study was the positive correlation between printing time and marginal discrepancy. Extended printing times correlated with higher dimension errors, implying that printing for a longer time may lead to cumulative polymerization or manufacturing errors. In the previous studies, a few studies have directly investigated fabrication time as an independent predictor, and Ellakany et al. (2025) reported that the type of printer, build orientation, layer thickness, post-processing procedures, and manufacturing parameters significantly affect the accuracy of IPs, consistent with the present study.[15]

Multiple regression analysis also showed that the greatest amount of variance in marginal discrepancy was explained by RMS deviation. This is biologically plausible, as the greater the 3-D distortion, the poorer the prosthesis adaptation. The same findings were obtained by Herguner et al. (2026), who found that manufacturing accuracy, measured by RMS deviation, exhibited a high correlation with both marginal and internal fit for various permanent 3D-printing resins for implant-supported crowns.[19]

High inter-examiner reliability (ICC>0.95) was found in the present study, suggesting that digital measurement protocols are highly reproducible for the assessment of prosthetic accuracy. This is consistent with the current digital prosthodontic studies that have suggested digital superimposition and stereomicroscopic measurement as accurate tools for evaluating the marginal discrepancy and trueness of implant-supported restorations.[15, 16]

In recent reports, it's also been reported that digital impressions make a significant contribution to the accuracy of prosthetics. Alfaraj et al. (2026) found that for most implant-supported prostheses, there is not much difference between the accuracy of digital impression techniques and conventional methods, except for full-arch restorations. The conclusions of this study validate the digital workflow used in the present investigation and highlight the clinical viability of the use of intraoral scanning and additive manufacturing.[20]

The results of the present study are consistent with recent published work which showed that 3D printing as a reliable manufacturing method for implant supported prostheses. Even though CAD/CAM milling remains the most precise method for manufacturing restorations, developments in printer resolution, printable materials, and post-processing protocols have significantly enhanced the clinical success of 3-D printed restorations. Therefore, especially in single-unit and short-span implant-supported rehabilitation, there is a predictable, cost-effective, and efficient alternative to conventional prosthodontics, but it still needs to be further developed in the case of full-arch rehabilitation.

There were a few limitations to the present study. The first is that it was an in vitro study, so there was no complete replication of the clinical variables like saliva, masticatory forces, thermal changes, and patient factors. Second, the evaluation was restricted to only one digital workflow (3D printing), one implant system, and a single printable material, which might not ensure the generalizability of the results to other implant systems, 3D printing technologies, or printable materials. Thirdly, the number of patients in the sample was rather small and recruited from a single facility. Lastly, only dimensional accuracy and fit of the implant-supported prostheses were evaluated, and no studies evaluated long-term clinical outcomes, including fracture resistance, wear characteristics, peri-implant tissue response, or implant survival. These findings should be confirmed with larger sample sizes, multicenter clinical studies, and longer follow-up in the future.

CONCLUSION

CAD/CAM milled implant-supported prostheses had significantly improved marginal adaptation, internal fit, and dimensional accuracy compared to 3D printed prostheses within the limitations of this study. However, most of the 3D-printed prostheses showed clinically acceptable marginal fit and passive indication, which makes it a reliable option for digital prosthodontics. The results indicate that additive manufacturing is a suitable, predictable, efficient, and cost-effective method for the fabrication of implant-supported restorations, but further optimization of printing parameters and materials is necessary to ensure the same accuracy as that of conventional milling methods.

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