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Evaluation of Fracture Strength and Surface Topography of Interim Prosthodontics Fabricated Using 3D Printing Compared to CAD/CAM Systems (In-Vitro Study)

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ABSTRACT

Background: In addition to the popularity of CAD/CAM milling systems, the use of 3D printing for the fabrication of interim prosthodontics has also become widespread. The materials used for 3D printing still need further investigation in regard to strength and surface topography. ***Objective:*** to evaluate fracture strength and surface topography of interim restorations fabricated by 3D printing systems compared to CAD/CAM milling systems. ***Materials and Methods:*** A preparation was performed on the first premolar and first molar of a mandibular typodont model cast to resemble a three-unit all-ceramic fixed dental prosthesis (FDP). A digital design was then created using ExoCad software to create a digital master model. Two groups of interim fixed dental prosthesis (IFDP) were fabricated based on the virtual design. Group I: eight IFDP samples of polymethyl-methacrylate (PMMA) were milled using CAD/CAM. Group II: Eight IFDPs were 3D printed using PMMA resin. The surface topography of samples was measured using a surface profilometer. The fracture strengths of the IFDPs were then assessed by a universal testing machine. ***Results:*** The difference in surface topography between both groups was statistically non-significant, as revealed by student t-test ($P=0.4499>0.05$). The milled group recorded a higher mean value of fracture strength than the 3D-printed group. Student t-test ($P=<0.0001<0.05$) revealed a statistically significant difference between both groups. ***Conclusions:*** PMMA IFPDs fabricated using CAD/CAM exhibited higher fracture strength than IFPDs fabricated using 3D printing. Both techniques produced restorations of comparable surface roughness.

Keywords: digital dentistry, interim restoration, milling, polymethyl methacrylate, three-dimensional printing

INTRODUCTION

A critical step in the fabrication of Fixed Dental Prosthesis (FDPs) is the fabrication of Interim Fixed Dental Prosthesis (IFDPs).[1] IFDPs serve to protect vital teeth from bacteria and sensitivity, preserve occlusion and phonetics, withstand mastication, and

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serve as aesthetic prototypes for patients to gain acceptance of or modify the proposed design.[2]

IFDPs are usually fabricated from monomethacrylate or dimethacrylate-based resins, and these materials are commonly used as provisional materials due to their ease of use, low cost, and good mechanical properties.[3-6] PMMA comes in a variety of forms, such as powder-liquid, prepolymer-ized blocks, and resin-based materials.[7-12]

The advancement of Computer-Aided Design (CAD) technology has facilitated the indirect manufacturing of IFDPs in a less labor intensive way, and with predictable results in terms of marginal and internal fit as well as aesthetics.[13-16] Milling machines waste excess material and are limited in the complexity of structures they can fabricate.[17, 18] Three-Dimensional (3D) printers, on the other hand, fabricate models using a variety of additive methods (AM), which could prove more cost-effective with the ability to create restorations with more complex details.[19]

The fabrication of restorations depends on factors such as the properties of the materials being used, the design of the product, the equipment and tools used in the fabrication process, and the environmental conditions during fabrication.[1,20-22] For example, some materials are more difficult to machine than others due to their hardness or toughness. The choice of milling tool and cutting parameters must take into account the properties of the material being milled in order to achieve the desired result.[1, 23]

With stereolithography (SLA) 3D-Printing, a laser is used to selectively solidify a liquid resin into a desired shape. Factors that can affect this process include the accuracy and precision of the laser, the properties of the resin, and the environmental conditions during printing.[24, 25] It is important to carefully control these factors in order to achieve the best possible results with SLA additive manufacturing.[26, 27]

Abad-Coronel et al [27] reported that intra-oral prosthesis should be made of a material that has high strength and rigidity. During the usage period, the mechanical properties of the IFDP material is affected by saliva, food, and beverages, as well as their interaction within the oral environment.[28, 29]

The surface topography of any dental restoration influences its mechanical properties; microscopic flaws and defects on the surface of dental ceramics have proven to statistically affect their strength characteri-stics.[30-33] Processing procedures such as polishing, finishing, and glazing have a direct effect on the mechanical properties of some dental materials, as many studies have shown.[32-35] Therefore, understanding and controlling surface topography is essential for achieving optimal functional and esthetic outcomes in an IFDP.[34, 36]

This study aims to evaluate fracture strength and surface topography of interim restorations fabricated by 3D printing systems compared to CAD/CAM milling systems. The first null hypothesis was that there would be no difference in the fracture strength between CAD/CAM milled and 3-D printed interim fixed dental prosthesis. The second null hypothesis was that there will be no difference in the surface roughness between CAD/CAM milled and 3-D printed interim fixed dental prosthesis.

MATERIALS AND METHODS

A total of sixteen samples were fabricated using two fabrication techniques. Group I: eight IFDP samples of polymethyl-methacrylate fabricated using a milling machine. Group II: eight IFDP samples of PMMA were fabricated using an SLA 3-D printer **(Table 1).** The first measurement test compares the surface topography of IFDPs from both groups using a surface profilometer, and image acquisition was performed for one sample from each group for image analysis. The second measurement test evaluates the fracture strength of IFDP samples from both groups.

Sample Size Calculation:

A power analysis was designed to have an adequate power to apply a two-sided statistical test of the null hypothesis that there is no difference in the fracture strength between CAD/CAM milled and 3-D printed interim fixed dental prosthesis. By adopting an effect size (d=1.51) - calculated based on the results of Zimmermann, Moritz, et al.[37] - an alpha (α) level of 0.05 (5%) and a beta (β) level of 0.20 (20%) i.e., power=80%; the predicted sample size (n) was found to be a total of 16 samples i.e., 8 samples per group. Sample size calculation was performed using G*Power version 3.1.9.4.[38, 39]

Abutment Preparation:

First, a lower typodont training model cast *(Banna, Egypt)* with acrylic teeth was used. The lower right first molar was removed to represent a short edentulous span requiring a three-unit FDP, and the socket was filled with wax to simulate gingival tissues underlying the pontic space.

Based on a standardized full-ceramic crown preparation, the lower right second molar and lower right second premolar were manually prepared to receive an all-ceramic zirconia FDP - with supragingival 1 mm wide shoulder finish lines with rounded internal line angles and a 12° uniform convergence angle.[40-42] A series of diamond burs were used - with the amount of reduction for each surface 2.0 mm occlusal reduction, 1.5 mm buccal and lingual reduction.[41, 42] Standardization of the preparations was checked using a periodontal probe and reduction matrix to verify the amount of reduction.[43, 44]

Digital Impression and Design:

A digital impression of the prepared typodont teeth was taken using a laboratory desktop scanner *(Medit T710, Seoul, Republic of Korea)***,** and a virtual cast was created.[45] The design featured two prepared abutments and a pontic space **(Figure 1)**.

The design of the IFDP samples utilized

Table (1): Materials, product names, manufacturers, fabrication techniques, and machines used.

Brand Name	Material Composition	Manufacturer	Fabrication Technique	Machine used for fabrication
CAD-IVORY	99% Polymethyl-methacrylate 1% Pigment	On Dent, Turkey	CAD/CAM Milling	Wieland Zenotec Select Hybrid
4K Resin	30% PMMA 56% EGDMA 14% MMA	Proshape, Turkey	SLA 3D Printing	3D Shining Accufab2B
Pro Model Resin	N/A	JamgHe, China	SLA 3D Printing	3D Shining Accufab2B

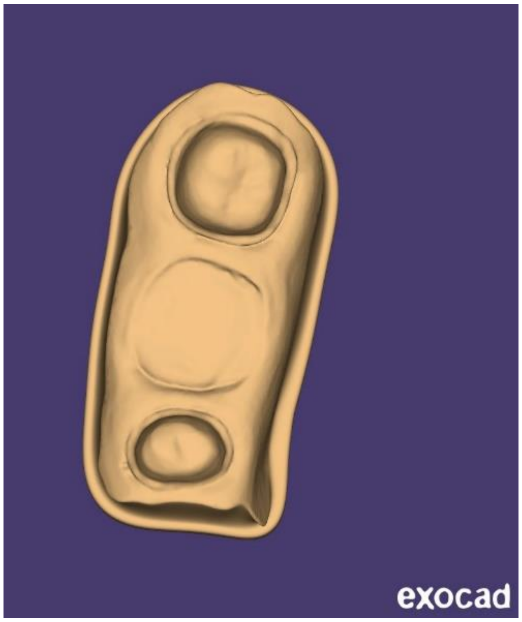

Figure (1): Virtual positive replica cast created in Exocad 3.0 Galway.

a shoulder finish-line design with rounded internal line angles, a connector size of 12 mm^2 as per manufacturer recommendations[45-47], an occlusal thickness of 2.0 mm, and a lingual and buccal wall thickness of 1.5 mm. The designs were made using Exocad 3.0 Galway and were saved as an STL file, which contained the data for the CAD reference model (CRM).

Printing of the Model Dies:

Sixteen resin model resin dies were fabricated using photopolymers *(Pro Model Resin, JamgHe, China)* and an SLA 3D

Printer *(Accufab2B, Shining 3D, Hangzhou, China)***.** Each model die contained two prepared abutments and a pontic space. The design of the dies featured a flat rectangular base, missing the lower right first molar, prepared lower second molar and second premolar.[37, 39]

Interim Fixed Dental Prosthesis Construction:

Milling the IFDPs (Group I):

Milling parameters were set on the milling software, with the disc thickness set at 14 mm, the drop height set to the disc surface, and the milling strategy of *PMMA 2.5_1 Bridge standard + 0.7 engraving + cut bars*. Eight IFDPs were milled using PMMA disks *(CAD-IVORY, On Dent, Turkey)* and CAD/CAM milling *(Wieland Zenotec Select Hybrid, Ivoclar, Schaan, Liechtenstein)* and were numbered. The material to be milled was selected as PMMA on the milling machine software, and the blank height was set as 14 mm. A sprue was set to be on the buccal surface of the pontics. The disk was then dismantled from the machine, and the sample was separated from the sprue using a diamond bur. The fit of the milled samples was checked on the model die with a dental explorer and magnifying loops with 3.5x magnification.

Printing the IFDPs (Group II):

The resin tank and cartridge were inserted into the 3D printer, and the cartridge was thoroughly agitated before insertion. The layer thickness was set to 0.05 mm per layer to achieve the highest level of accuracy with optimum speed. The samples were oriented horizontally with the occlucal surface facing the build platform. Eight IFDPs were 3D-Printed using PMMA material *(4K Resin TEMP, Proshape, Turkey)* and an SLA 3D Printer *(Accufab2B, Shining 3D, Hangzhou, China)* and were numbered. Eight IFDP samples were then printed using PMMA resin. The printed samples were rinsed with isopropyl alcohol (IPA, 90%) for 3 minutes as per the manufacturer's instructions, in order to fully clean the uncured resin and facilitate removal. The IFDPs were then allowed to fully dry, then the build platform was removed using flush cutters. The fit of the printed samples was initially checked on a reference model die with a dental explorer and magnifying loops with 3.5x magnification.

Post-processing:

Regarding group I (milled), after removing the sprue from the IFDP samples using a diamond bur, the surface of the pontic was finished using a bench lathe for two minutes.

As for group II (3D printed), the 3D printed IFDPs were removed from the build platform, and the support surface of the printed samples was finished using soflex and rubber discs. The IFDP was then placed for 2 minutes into a light curing unit *(Fab Cure, Shining 3D, Hangzhou, China*) as per the manufacturer's instructions. Final polishing was done using a bench lathe for two minutes.

Seating of the Samples:

All samples were tried-in for seating on the model dies to make sure they were clinically acceptable, with good marginal adaptation, and had no rocking. Samples were checked on the model dies for rocking using alternate finger pressure, tactile sensation, direct vision, and a dental explorer and magnifying loops with 3.5x magnification.[48, 49]

Measuring Surface Topography:

The surface roughness of IFDPs from both groups was measured using a surface profilometer *(SJ- 210 Surface roughness tester, Mitutyoyo Japan).* The specimen was fitted to the specimen holder in which the surface to be measured was placed in a horizontal direction. The specimen holder then moved in a vertical direction up to the specimen surface, with just the measuring tip coming into contact. Device calibration is done using the standard calibration specimen before use.[50] The optical methods tend to fulfill the need for quantitative characterization of surface topography without contact. The images were taken from one sample from each group with the following image acquisition system: Digital camera (U500x Digital Microscope, Guangdong, China) with 3 Mega Pixels of resolution, placed vertically at a distance of 2.5 cm from the samples. The cropped images were analyzed using WSxM software *(Ver 5 develop 4.1, Nanotec, Electronica, SL)*[51] where all limits, sizes, frames, and measured parameters are expressed in pixels. A 3D image of the surface profile of the specimens was created with the central area and in the sides at area of 10 µm × 10 µm.[52]

Temporary Cementation of IFDPs

Each sample was temporarily cemented onto its model die prior to fracture strength testing, using a zinc oxide non-eugenol temporary cement *(Cavex Temporary Cement, Cavex, Haarlem, The Netherlands).* The purpose of temporary cementation is to simulate the clinical scenario. IFPDs were placed under a static load of 2 KG during the setting of the cement to ensure complete seating of the restorations on the dies using a custom-made loading device. Subsequently, the cement was allowed to be set for two minutes according to the manufacturer's instructions, and excess cement was scrapped with an explorer while visually checking that residual cement was removed.[53, 54]

Measuring Fracture Strength:

The samples were individually mounted on a computer-controlled materials testing machine *(Model 3345; Instron Industrial Products, Norwood, MA, USA)* with a load cell of 5 kN. Data was recorded using computer software *(Bluehill Lite Software, Instron®)*. Each sample was secured to the lower fixed compartment of the testing machine by tightening screws. A fracture strength test was done by compressive mode of load applied onto the central fossae of the occlusal surface of the pontic, using a metallic rod with a round tip (9.6 mm diameter) attached to the upper movable compartment of testing machine travelling at a crosshead speed of 1 mm/min with tin foil sheet in-between to achieve homogenous stress distribution and minimization of the transmission of local force peaks. The diameter of 9.6 mm for the round tip was chosen to adequately cover the pontic's occlusal surface. The load at failure manifested by an audible crack and confirmed by a sharp drop at the load-deflection curve recorded using computer software *(Bluehill Lite Software Instron® Instruments)*. The load required to fracture was recorded in Newton.

Mode of Failure:

Failure modes were observed and recorded **(Figure 2).** They were classified according to the site of fracture into molar-molar, molar-premolar, molar, and premolar.[55-58] The purpose is to visually observe and record the fracture line and the incidence of connector to retainer fractures.

Figure (2): CAD/CAM IFDP Mode of Failure (premolar-molar connector).

Data Analysis:

Data from both groups were collected and arranged using Excel for Microsoft office (version 365). Data were explored for normality by checking the data distribution and using Kolmogorov-Smirnov and Shapiro-Wilk tests. Student t-test was used to verify whether there was a statistical difference between groups in terms of roughness and failure load results. The Chi square test was done between failure patterns. A correlation between roughness and fracture was found using Pearson linear correlation.

Statistical analysis was performed using Graph-Pad Instat statistics software (version 3.06) for Windows. P values $\leq$ 0.05 were statistically significant in all tests. The sample size (n=8/group) was large enough to detect large effect sizes for main effects and pair-wise comparisons, with a satisfactory level of power set at 80% and a 95% confidence level.

RESULTS

Fracture strength test:

Descriptive statistics showing mean values and standard deviation of fracture strength test results measured at failure load (Newton) for both groups are summarized **(Table 2)** and graphically drawn **(Figure 3).**

It was found that the milled group recorded a higher mean ± SD value of fracture resistance load (749.91±93.01 N) than the 3D Printed group mean ± SD value (319.41±48.73 N). The difference between both groups was statistically ***significant,*** as revealed by student t-test (P=<0.0001<0.05).

Mode of failure:

Evaluations were based on two main types, and two subtype modes were listed **(Table 3)** and graphically drawn. For both groups, failure mode was predominantly at the premolar-molar connector area with an intermediate percentage at the molar-molar connector, while a minority of samples showed retainer failure. The difference in the

Table (2): Comparison of fracture resistance results (Mean values± SDs) as function of fabrication technique.

Variables		***Mean ± SDs***	***95% CI***		***Statistics***
			Low	***High***	
Fabrication technique	*3D Printed group*	***319.41±48.73***	278.67	360.15	***P value***
	Milled group	***749.91±93.01***	672.15	827.67	<0.0001*

** Significance level at p< 0.05.*

Table (3): Frequent distribution of failure mode patterns for both groups.

Variable		***Failure sites***				***Statistics***
		Connector		***Retainer***		***Chi test***
		Premolar-molar	***Molar-molar***	***Premolar***	***Molar***	***P value***
Fabrication Technique	*3D Printed group*	5 (62.5%)	2 (25%)	1 (12.5%)	0 (0%)	0.5041 (ns)
	Milled group	4 (50%)	3 (37.5%)	0 (0%)	1 (12.5%)	

significance level at p< 0.05.
(ns); non-significant

failure modes between both groups was statistically non-significant, as proved by the chi square test (p=0.5041>0.05).

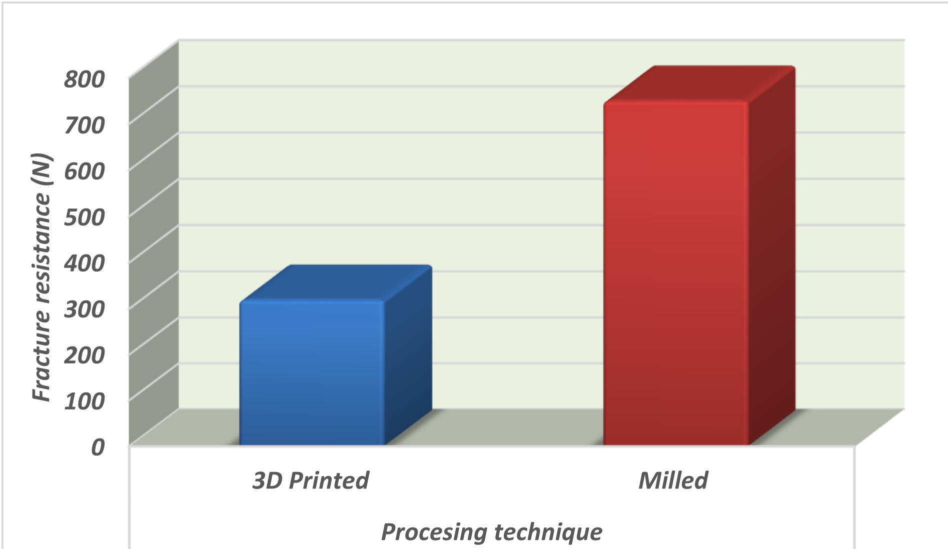

Figure (3): Column chart comparing between fracture resistance mean values for both groups.

Surface Topography:

Surface Profilometer

Roughness average (Ra) results (Mean±SD) measured in microns (µm) for both groups, as a function of fabrication technique, are summarized **(Table 4, Figure 4)**.

Table (4): Comparison of roughness average results (Mean values± SDs) as function of fabrication technique.

Variables		*Mean ± SDs*	*95% CI*		*Statistics*
			Low	*High*	
Fabrication Technique	*3D Printed group*	*1.2599±0.3014*	1.0079	1.5119	*P value*
	Milled group	*1.1338±0.1910*	0.9741	1.2935	0.4499 (ns)

significance level at p< 0.05.
(ns); non-significant

It was found that the 3D Printed group recorded a higher mean ± SD value of roughness average (1.2599±0.3014 µm) than the milled group mean ± SD value (1.1338±0.1910 µm). The difference between both groups was statistically non-significant, as revealed by the student t-test (P=0.4499>0.05).

Image Analysis:

3D images of the surface profile of the specimens were created **(Figures 5 & 6)**. The examination of the 3D images showed notable similarities with no discernible statistically significant differences between the two fabrication techniques. The surface pattern of the IFDPs appeared similar in both groups, with a slightly lower peaks and shallower valleys for the CAD/CAM milled group.[32, 59]

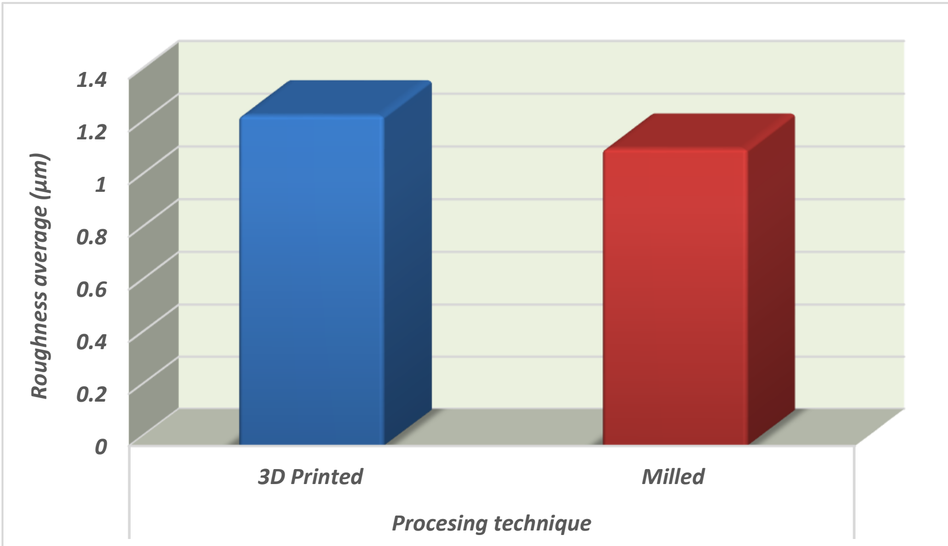

Figure (4): Column chart comparing between roughness average mean values for both groups.

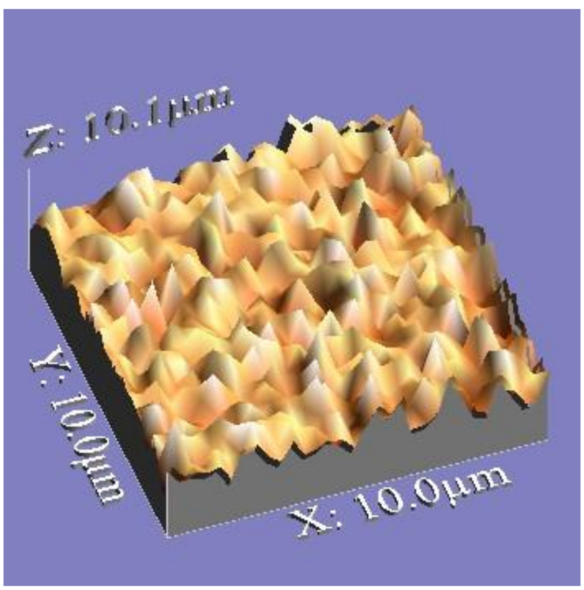

Figure (5): Three dimensional image showing surface roughness for milled group.

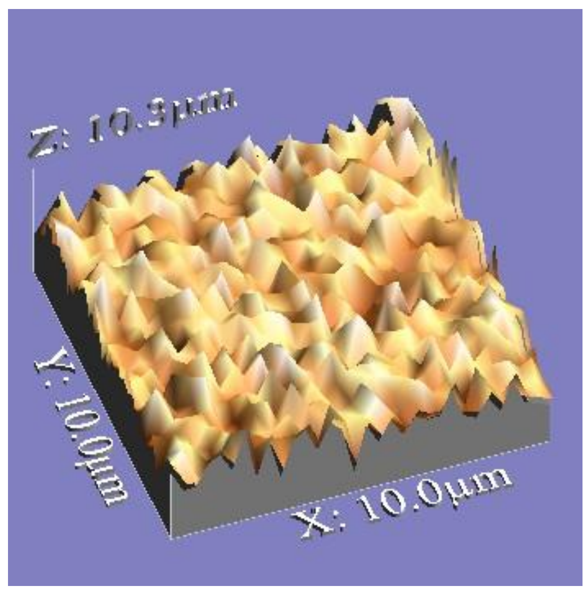

Figure (6): Three dimensional image showing surface roughness for 3D printed group.

Correlation between roughness and fracture:

It was found that there was a non-significant inverse correlation between **roughness and fracture** as indicated by Pearson linear correlation (Correlation coefficient (r) =-0.4276, r^2= 0.1828 and p=0.2907> 0.05).

DISCUSSION

Polymeric resins can be fabricated using various techniques, including CAD/CAM milling and 3D printing. PMMA (polymethyl methacrylate) is a commonly used acrylic resin for interim fixed dental prosthesis as it has good mechanical properties and color stability.[4-6, 9, 10] The common applications of PMMA in prosthodontics provided a strong basis to fabricate all samples in the current study from the material composition of PMMA, with their indication of use being provisionalization.

The nature of these materials may still vary widely in terms of packaging, composition, and physical properties. The higher physical property value related to milled IFDPs can be attributed to several factors such as the homogeneity of CAD/CAM blocks and discs which is difficult to achieve with conventional methods. CAD/CAM also offers a high degree of precision in the manufacturing of the restorations.[14-17]

Factors such as load rate, frequency, environment, and storage medium could affect the IFDP's overall clinical performance.[26] Furthermore, the composition of PMMA and the addition of fillers significantly affect its physical properties.[25, 27] In the same light, different forms of PMMA, whether discs or liquid resin, would also appear to have an effect on PMMA's performance in a clinical setting. Surface roughness is another important factor to consider when constructing an interim fixed dental prosthesis. High surface roughness can lead to increased plaque accumulation, compromised esthetics, and patient discomfort. There are no specific universal standards or guidelines for the roughness average of interim fixed dental prostheses. Achieving an acceptable roughness average for the surface of an interim fixed dental prosthesis can vary depending on the materials used, the manufacturing process, and patient preference.

The effect of fabrication technique on the fracture strength of polymethyl methacrylate (PMMA) has been tested across different studies.[7, 8, 16, 27] It was found that CAD/CAM milled PMMA exhibited a higher fracture load than conventionally manufactured PMMA.[16] Both CAD/CAM and 3D printing systems are capable of utilizing PMMA to create accurate and detailed IFDPs; thus, CAD/CAM's fabrication efficacy should be tested against that of 3D printing in order to derive accurate conclusions and make informed clinical decisions.

When choosing an impression technique, the choice for the current study was between conventional and digital optical impressions. The current study utilized optical scanning because the digital impression process offers several advantages over conventional impressions. This allowed for accurate replication of prepared abutments, particularly when taking impressions for single-tooth restorations and three-unit fixed dental prostheses.[45] Furthermore, this would also streamline the design and fabrication process digitally.

The design of the IFDPs determines the characteristics and dimensions of the restorations. One study reported that for endodontically treated maxillary premolars restored with ceramic endocrowns, proximal box elevation (PBE) increases fracture strength but not microleakage.[46] This could be attributed to the shorter lever arm provided by a fulcrum close to the area of load application. This further signifies the impact that design has on the mechanical properties and clinical performance of the restoration.

Therefore, the current study utilized a connector size of 12 mm² to ensure the stability and structural integrity of the IFDPs.[47] The IFDPs were also designed with a shoulder finish-line to accommodate the prepared abutments.

Sixteen resin model dies were selected for this study to seat and support the IFDPs for fracture testing. This is in line with the methodology used in other studies where identical resin dies are fabricated to receive permanent crowns and bridges. The resin model dies were fabricated to standardize the abutment dimensions and durability during fracture strength testing of the PMMA IFDP samples.[39]

The first null hypothesis, that there would be no significant difference between the fabrication techniques in terms of fracture strength, was rejected. The second null hypothesis that there would be no significant difference between fabrication techniques in terms of surface topography, was approved.

The results of the current study's fracture strength tests indicate that CAD/CAM milled PMMA interim fixed dental prosthesis have a significantly higher fracture strength than 3D printed PMMA interim FDPs, as they recorded much higher mean loads. This is in line with previous studies that have shown that CAD/CAM milled PMMA restorations have significantly higher mechanical properties than 3D printed PMMA restorations.[8, 11, 23, 27] This may be due to the PMMA discs used in CAD/CAM milling are manufactured under high pressure and temperature, which results in better physical and mechanical properties.[18] The material composition of the discs also contains a higher percentage of pure PMMA (99%) compared to the 3D printed resin, which contains other acrylates as well (56% EGDMA, 14% MMA).

The higher homogeneity of PMMA discs could also play a significant role in CAD/CAM milled IFDPs' fracture strength. The inclusion of other methacrylates in the composition of PMMA resin helps facilitate SLA 3D printing. By reducing the PMMA content of the resin, a lower viscosity can be achieved. PMMA based resins containing more than 50% weight PMMA could not be printed owing to its high viscosity. Furthermore, higher concentrations of PMMA tend to form aggregates in the resin, significantly increasing their viscosity.[25, 27]

Mode of failure evaluation showed that the connector areas were more susceptible to fracture, and this is in line with previous studies that show that the mode of failure for FPDs is predominantly around the bridge connectors, which is a common failure point for interim fixed dental prosthesis.[7, 16, 27, 58] This indicates that the connector design and fabrication technique play a crucial role in the fracture strength of interim fixed dental prosthesis.

The surface roughness tests conducted in our study did not reveal a significant correlation between roughness and fracture strength. Thus, surface roughness may not be a critical factor influencing the fracture strength of interim fixed dental prosthesis. It is also worth noting that the surface roughness of 3D printed resin may be influenced by the thickness of the printed layers, with thinner layers resulting in a smoother surface after polishing.[33] Nonetheless, surface roughness values of the 3D printed PMMA resin were found to be superior to that of conventional interim restorations and are considered clinically acceptable.[33-36]

Image analysis was utilized to produce a more comprehensive overview of surface topography, offering additional insight into the contributing factors influencing fracture strength to complement surface profilometry measurement. The examination of the 3D images showed notable similarities with no discernible statistically significant differences between the two fabrication techniques. The surface pattern of the IFDPs appeared similar in both groups, with slightly lower peaks and shallower valleys for the CAD/CAM milled group; this is in line with the statistical non-significance found in the quantitative analysis of the roughness average (RA), further emphasizing the comparable surface topographies produced through these two fabrication techniques.[33, 59]

Increasing the sample size would enhance the statistical power and reliability of the findings. Future studies could explore other fabrication methods and materials for interim fixed dental prosthesis. The design of the preparation and finish line placement can also be explored in terms of fracture strength. Long-term clinical studies can help evaluate the performance of interim fixed dental prosthesis fabricated using different techniques and materials.

CONCLUSIONS

Within the limitations of the present study, the following points could be concluded:

1. CAD/CAM milling is the superior choice for the fabrication technique of polymethyl methacrylate (PMMA) resin interim fixed dental prosthesis.
2. CAD/CAM milled and 3D printed interim fixed dental prosthesis were comparable regarding surface roughness.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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