Fit Accuracy of Removable Partial Denture Frameworks Fabricated from 3D-Printed Resin Patterns Versus Selective Laser Melting

by

Nadine Ziad Mirza

BS, University of Maryland College Park, 2015

DDS, University of Maryland School of Dentistry, 2019

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This thesis was presented

by

Nadine Ziad Mirza

It was defended on

August 2, 2022

and approved by

Thomas Kunkel, DMD, Chair and Residency Program Director, Assistant Professor, Department of Prosthodontics

Heidi Huber, DMD, MS, Assistant Professor, Department of Prosthodontics

Thesis Advisor: John Ference, BA, DMD,MPH, MSS, MDS, FACP, Assistant Professor and Clinical Director, Undergraduate Department of Prosthodontics

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Nadine Ziad Mirza, DDS

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Abstract

Statement of Problem: Fit accuracy is not only essential to the success of prosthodontic rehabilitation with removable partial dentures (RPDs) but is also necessary to prevent trauma to the oral hard and soft tissues. Questions remain whether the fit accuracy of digitally fabricated RPD frameworks is comparable to those fabricated by more conventional techniques.

Purpose: The aim of this study was to compare the fit accuracy of RPD frameworks fabricated by 3D-printed resin pattern casting versus those fabricated by selective laser melting (SLM). The null hypothesis is that there is no significant difference in the fit accuracy: (1) between 3D printed castable resin patterns and SLM-printed frameworks, and (2) among the 4 areas measured under the framework (rest, retentive arm, bracing arm, major connector) within each group.

Materials and Methods: A mandibular metal reference model was milled and used for the simulation. Scanning of the model was performed using a desktop scanner. The framework was designed using CAD software. The 3D-printed resin patterns were fabricated using an SLA printer and casting was performed to fabricate the SLA-Cast frameworks. A direct metal printing machine was used to generate the SLM framework. Fit accuracy of the two groups was performed using silicone impression material and digital calipers to measure the mean vertical gaps. The independent t test was used to compare the mean vertical gaps between the 2 groups. Within each group, all 4 measured areas were compared using one-way ANOVA.

Results: A clinically acceptable fit was achieved at the clasps and rests, regardless of the production method used. The overall mean vertical gaps were significantly different between the SLA-Cast and SLM frameworks – with greater gaps in the SLM frameworks. The mean vertical gaps at the 4 measured areas within the same group were all found to be significantly different from each other as well.

Conclusion: The 0.12-mm difference in overall mean vertical gaps between SLA-Cast and SLM-frameworks may have no clinical significance. The greatest discrepancy in fit accuracy was observed under the major connector. There is still room for improvement in the adaptation of RPD frameworks fabricated through a digital workflow.

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Preface

I would like to thank my committee team, Dr. Kunkel, Dr. Ference and Dr. Huber for their oversight and guidance throughout residency and my thesis project. I would also like to thank my co-residents, Dr. Al-Rasheed and Dr. Dashti, for being there every step along the way and for always serving as a source of inspiration and motivation – and most importantly as good friends. Lastly, thank you to my family for their encouragement and unyielding support.

1.0 Introduction and Statement of the Problem

Rehabilitation with removable partial dentures (RPDs) is a cost-effective and less invasive treatment option for the partially edentulous population. It is especially helpful in cases with no terminal abutment, long edentulous spans, or severely resorbed residual ridges (Bajunaid et al., 2019). Patients of lower socioeconomic means or who present with a complicated medical history of chemoradiation therapy or bone targeted therapy, such as bisphosphonates, may also be better candidates for conventional RPDs over implant-supported prostheses (Rokhshad et al., 2022). With advents in oral hygiene protocols and fluoridation, the prevalence of tooth loss has decreased, necessitating greater treatment of partially edentulous patients as opposed to those that are completely edentulous (Slade et al., 2014). In North America alone, the number of partially edentulous patients is expected to increase to 200 million over the next 15 years, and the need for RPDs is already burgeoning nationwide (Kim, 2019).

Fit accuracy is essential to the successful retention, stability and support of any removable dental prosthesis that strives to restore function, esthetics, and phonetics. Adequate function, therefore, depends on adequate fit. Poor fit is also one of the primary reasons why patients discontinue RPD wear (Benso et al., 2013). RPDs may be considered the ultimate test of fit accuracy for a digital workflow because RPD framework fabrication involves capturing both hard and soft tissue anatomy accurately. Gaps between the prosthesis and mucosa, or between the prosthesis and dentition, not only compromise the biomechanics of the framework, creating greater patient discomfort and tissue damage, but also create potential plaque-retentive food traps, that could incite fungal and bacterial infections (Rokhshad et al., 2022; Tregerman et al., 2019).

Although many studies in the literature have quantitatively compared the fit accuracy of digitally fabricated Co-Cr alloy RPD frameworks to those fabricated by more conventional casting methods, few studies have compared direct 3D printing to a combined analog-digital technique involving castable 3D-printed resin patterns (Arnold et al., 2018; Bajunaid et al., 2019; Chen et al., 2019; Rokhshad et al., 2022; Soltanzadeh et al., 2019; Tasaka et al., 2020; Tregerman et al., 2019; Ye et al., 2017). More studies are needed to compare the fit and clinical outcomes of RPD frameworks fabricated through combined analog-digital workflows involving rapid prototyping techniques.

2.0 Specific Aims

Aim 1: Fabricate a milled metal reference model for accurate fit testing.

Aim 2: Use CAD software to survey and design an RPD framework that is suitable for direct metal printing and castable resin pattern printing.

Aim 3: Export CAD design to an SLA printing machine to fabricate a castable 3D-printed resin pattern to be cast conventionally (SLA-Cast framework).

Aim 4: Export CAD design to an SLM machine for direct metal framework printing (SLM framework).

Aim 5: Assess fit accuracy of SLA-Cast and SLM frameworks on the metal reference model using PVS impression material and digital calipers

3.0 Background and Literature Review

3.1 Conventional Lost Wax Technique

The conventional lost wax (CLW) technique has historically been the primary method of fabricating RPD metal frameworks. In this technique, RPDs are made by casting from the manual waxing of a framework on a refractory cast (Carneiro et al., 2021). Conventional casting methods are complex, time-consuming, expensive, and prone to cumulative human errors during processing (Rokhshad et al., 2022, Rudd, 2001). These processing errors are often related to the precise placement of the investment molds in the burn out oven and casting machine, and the use of accurate temperatures and times (Rudd, 2001). The propagation of such errors could lead to wax pattern and refractory cast distortions, resulting in gaps and misfits which can contribute to patient discomfort and damage to the hard and soft tissue (Tregerman et al., 2019). It is, therefore, essential to investigate and apply new RPD framework fabrication methods

3.2 CAD/CAM Overview

Computer-aided designing and computer-aided manufacturing (CAD/CAM) were first implemented in dentistry in 1990 and have since revolutionized prosthodontic rehabilitation with fixed and implant-supported prostheses but is more recently gaining traction in removable appliances (Rokhshad et al., 2022). Although CAD/CAM technologies help reduce errors during laboratory and clinical procedures with greater time effectiveness and patient acceptability, they have a steep initial cost and learning curve (Ahmed et al., 2021; Bilgin et al., 2016; Carneiro et al., 2021; Rokhshad et al., 2022; Soltanzadeh et al., 2019; Tregerman et al., 2019; Ye et al., 2017).

CAD/CAM technologies encompass both additive and subtractive techniques and have been used in RPD therapy to make digital casts, survey, design, scan, and print 3D prostheses or castable resin patterns (Rokhshad et al., 2022; Tregerman et al., 2019). In comparison to subtractive milling methods, additive printing is not only more economical and less wasteful of materials, but also allows for the formation of complex 3D geometries directly from digital designs (Bajunaid et al., 2019; Bohnenkamp, 2014; Rokhshad et al., 2022; Van Noort, 2011). There are currently two main ways to leverage CAD/CAM technologies for RPD metal framework fabrication. The first uses additive techniques to fabricate a 3D-printed resin pattern, which is then cast via the lost-wax method (Tasaka et al., 2021). The second uses additive manufacturing with metal alloys to directly fabricate metal RPD frameworks (Tasaka et al., 2021). Both these techniques take advantage of the speed and efficiency of rapid prototyping (RP).

3.3 Rapid Prototyping Overview

Examples of RP technologies include selective laser melting (SLM), selective laser sintering (SLS), stereolithography (SLA), digital light projection (DLP), and direct inkjet printing (DIP) (Ahmed et al., 2021; Bajunaid et al., 2019; Rokhshad et al., 2022; Tasaka et al., 2020; Tregerman et al., 2019).

SLM is an additive manufacturing technique for metallic alloys that uses a high-power laser beam to completely melt and consolidate metal powder into successive layers (Bajunaid et al., 2019; Van Noort, 2011; Tregerman et al., 2019). SLS is similar to SLM, but in SLS thermal energy is used to partly melt, or sinter, the metal powder into the framework shape (Tasaka et al., 2021). Both SLS and SLM can, therefore, be used to print cobalt-chromium (Co-Cr) alloy or even titanium frameworks. SLA, on the other hand, is an additive technique that uses ultraviolet (UV) lasers to polymerize photosensitive resin materials in small layers 10 to 100 microns thick (Tregerman et al., 2019). SLA manufacturing can be used to fabricate diagnostic casts, resin wax patterns, resin RPD frameworks, provisional restorations, denture record bases and teeth, and surgical guides (Revilla-León & Özcan, 2019; Tregerman et al., 2019). DLP is similar to SLA, but with faster processing since an entire layer can be polymerized at once (Tregerman et al., 2019). Jet printing emits thin streams of resin material onto a build platform to incrementally create layers that are then polymerized using a UV light source (Ahmed et al., 2021).

Dental laboratories are currently using additive techniques to digitally manufacture RPD frameworks in metal. SLM manufacturing in particular has been shown to produce clinically acceptable RPD frameworks with possibly better mechanical properties than cast or milled frameworks (Bajunaid et al., 2019; Ye et al., 2017; Zhou et al., 2017).

3.4 Comparing Digital to Analog Methods

Despite their long-term time- and cost-saving implications, there is still much controversy in the literature regarding the fit accuracy of RPD frameworks fabricated from fully digital or combined analog-digital workflows in comparison to conventionally cast RPD frameworks. To the author's best knowledge, there are 2 current clinical studies and 6 current in vitro studies relevant to assessing the fit accuracy of digitally fabricated Co-Cr alloy RPDs; the main parameters and results of these 8 articles are summarized in Table 1 (Arnold et al., 2018; Bajunaid et al., 2019; Carneiro et al., 2021; Chen et al., 2019; Rokhshad et al., 2022; Soltanzadeh et al., 2019; Tasaka et al., 2020; Tregerman et al., 2019; Ye et al., 2017). Based on this review, the majority of studies in the literature have suggested that the fit accuracy of digitally fabricated RPD frameworks is either comparable or slightly inferior to conventionally cast frameworks (Arnold et al., 2018; Carneiro et al., 2021; Chen et al., 2019; Rokhshad et al., 2022; Soltanzadeh et al., 2019; Ye et al., 2017). Many of the studies that found a misfit difference between the analog and CAD/CAM methods, however, did not deem the difference clinically significant as the digital frameworks still resulted in adequate retention, stability, and fit (Chen et al., 2019; Rokhshad et al., 2022; Soltanzadeh et al., 2019; Ye et al., 2017). The type of CAD/CAM technique employed, subtractive or additive, may also affect RPD framework fit as Arnold et al. demonstrated that RP techniques tend to show distinct fitting irregularities, while milling showed significantly better fit in comparison to analog methods (Arnold et al., 2018). According to a recent systematic review, in vitro studies tend to demonstrate clinically acceptable fit accuracy, while clinical trials showed heterogeneity in results likely due to different fit assessment methods (Carneiro et al., 2021; Tregerman et al., 2019; Ye et al., 2017).

Comparing digital to conventional methods	Study	Type of Study	Evaluated Arch	Assessment Method	**Results** (with mean or range misfit if appliable, mm)
Comparable or slightly inferior fit compared to analog or combined analog-digital method, but not clinically relevant	Ye et al., 2017	Clinical study	Kennedy class I, II, III, & IV	Clinical replica technique with silicone impression material	CLW vs. SLM
	Chen et al., 2019	In vitro	Maxillary Kennedy class I, II, III, & IV	Clinical replica technique with silicone impression material, then scanned & used reverse engineering software	For Kennedy class I: CLW (0.17) vs. SLM (0.29)
	Soltanzadeh et al., 2019 ***	In vitro	Maxillary Kennedy class III Mod I	Color mapping & metrology software	CLW (0.027) vs. printed castable resin (0.005) vs. SLM from stone model (0.16) vs. SLM (0.15)
	Rokhshad et al., 2022	In vitro	Maxillary Kennedy class III Mod I	Superimposition software	CLW (0.103) vs. printed castable resin (0.109)
Inferior fit compared to analog method & clinically relevant	Arnold et al., 2018 ***	In vitro	Maxillary Kennedy class III Mod II	Light microscopy	CLW (0.073) vs. direct milling (0.038) vs. indirect milling (0.045) vs. printed castable resin (0.112) vs. SLM (0.363)
Significantly better fit compared to analog or combined analog-digital method	Bajunaid et al., 2019	In vitro	Mandibular Kennedy class III, Mod I	Digital microscope	CLW (0.175) vs. SLM (0.173)
	Tregerman et al., 2019	Clinical study, cross sectional	Kennedy class I, II, & III	Questionnaires	CLW vs. printed castable resin vs. SLM with analog impressions vs. SLM with scanning
	Tasaka et al., 2020	In vitro		Superimposition software	Printed castable resin (-0.185 to 0.352) vs. SLS (-0.166 to 0.123)

Table 1 Main results of articles included in this literature review

CLW: Conventional Lost Wax technique; SLM: Selective Laser Melting; SLS: Selective Laser Sintering; *** denoting analogous studies comparing printed castable resin vs. SLM

Digital RPD manufacturing is still in its infancy, but as the number of available designing software programs increases and the manufacturing technology advances, opportunities for greater overall fit and accuracy improve. More recent studies – including a recent systematic review – suggest superior fit accuracy of completely digitally fabricated RPD frameworks over analog or combined analog-digital methods (Ahmed et al., 2021; Bajunaid et al., 2019; Tasaka et al., 2020, Tregerman et al., 2019). In an in vitro study by Bajunaid et al., the rest seats of 3D-printed metal frameworks showed significantly better fit accuracy than did those made by the CLW technique

(Bajunaid et al., 2019). They concluded that the SLM manufacturing of metal frameworks is a promising technique for routine clinical practice (Bajunaid et al., 2019). An in vitro comparison of the fit accuracy between castable 3D-printed resin pattern frameworks (a combined analog-digital method) and SLS metal printed frameworks (a fully digital method) suggested a significant difference at the rests, proximal plates, connectors, and clasp arms with greater variation in the combined workflow than in the completely digital SLS printed group (Tasaka et al., 2020). Switching between analog and digital pathways may introduce a compounding of errors at each step (Rokhshad et al., 2022; Tasaka et al., 2020).

A clinical study by Tregerman et al. also confirmed that a fully digital workflow – involving intraoral scanning, designing, and SLM printing – was significantly better than a completely analog or even a combined analog-digital workflow for RPD framework fabrication (Tregerman et al., 2019). Tregerman et al. attributed the high performance of the fully digital workflow to the greater clinical success and accuracy of intraoral scanning compared to traditional impressions (Tregerman et al., 2019). The weakest link in combined workflows for RPD fabrication is likely at the impression stage, which may be overcome with digital scanning provided that the tissue morphology is favorable. The literature, however, is divided when it comes to the accuracy of full-arch scanning (Ender & Mehl, 2011 & 2015; Hayama et al., 2018; Kattadiyil et al., 2014; Keul & Güth, 2020; Schmidt et al., 2020). More recent articles seem to support digital scanning as having comparable accuracy to conventional impressions, especially when used for hard tissues (Ender & Mehl, 2011; Hayama et al., 2018; Keul & Güth, 2020). If a fully digital workflow is to be used, then case selection for 3D-printed RPD prostheses is, therefore, of the utmost importance.

When it comes to case selection, the length of the edentulous span and the Kennedy classification design of the prosthesis are important factors to assess because they may play a role in the accuracy of CAD/CAM techniques (Bajunaid et al., 2019; Chen et al., 2019). Bajunaid et al., for example, found that the rest seat fit accuracy for the SLM technique was significantly better in long edentulous spans compared to short edentulous spans, but the edentulous span length made no significant difference in fit accuracy in the CLW technique (Bajunaid et al., 2019). Alternatively, Chen et al. found that conventional casting resulted in greater adaptation than SLM-printing for frameworks with large spans and more retainers and claps, which was corroborated by Soltanzedeh et al.'s study (Chen et al., 2019; Soltanzedeh et al., 2019). Kennedy class III designs typically require more retainers and clasping features than do Kennedy classes I and II designs. Tregerman et al., however, found no significant difference among Kennedy classifications when comparing the fit accuracy of digitally versus conventionally fabricated RPD frameworks (Tregerman, 2019).

Many other studies in the literature, however, do suggest that Kennedy class III designs have the largest discrepancies and misfits (Al Mortadi et al., 2020; Arnold et al., 2018; Bajunaid et al., 2019; Rokhshad et al., 2022; Soltanzedeh et al., 2019; Tasaka et al., 2020; Tregerman, 2019). In areas of extensively moveable soft tissue or wide arches, a fully digital workflow with intraoral scanning could also potentially be a source of error (Tregerman, 2019). A recent clinical study, therefore, advised caution when scanning Kennedy classes I and II for digitally fabricated RPD frameworks (Tregerman, 2019).

Across the literature, the method of fit accuracy assessment is often not standardized in a single non-subjective technique. The resulting heterogeneity in fabrication and assessment methods, materials used, and the complexity of RPD designs confounds cross-study comparisons and may account for some of the variation in holistic results (Carneiro et al., 2021; Chen et al., 2019; Rokhshad et al., 2022). Despite improvements in scanning and digital manufacturing, questions therefore remain regarding the fit accuracy of 3D-printed RPD frameworks versus those conventionally cast from either stone or a 3D-printed resin pattern.

4.0 Purpose of The Present Investigation

The purpose of this study is to quantitatively assess the fit accuracy of Co-Cr alloy RPD frameworks fabricated by either a combined analog-digital technique involving 3D-printed resin pattern castings, or a fully digital technique involving SLM-printed metal frameworks. The fit accuracy was assessed by the mean vertical gaps between the frameworks and the metal reference model. The null hypothesis is that there is no significant difference in the fit accuracy: (1) between 3D printed castable resin patterns and SLM-printed frameworks, and (2) among the 4 areas measured under the framework within each group.

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5.0 Material and Methods

This study was conducted at the University of Pittsburgh School of Dental Medicine. The sample size for this in vitro study was originally modeled following Bajunaid et al.'s study using an independent t test, but due to limited resources a smaller sample size had to be used (Bajunaid et al., 2019). A total of 12 frameworks were fabricated, consisting of 6 SLA-Cast frameworks and 6 SLM frameworks. An overview of the methodology and of the workflow for the two fabrication methods is depicted in Figure 1.

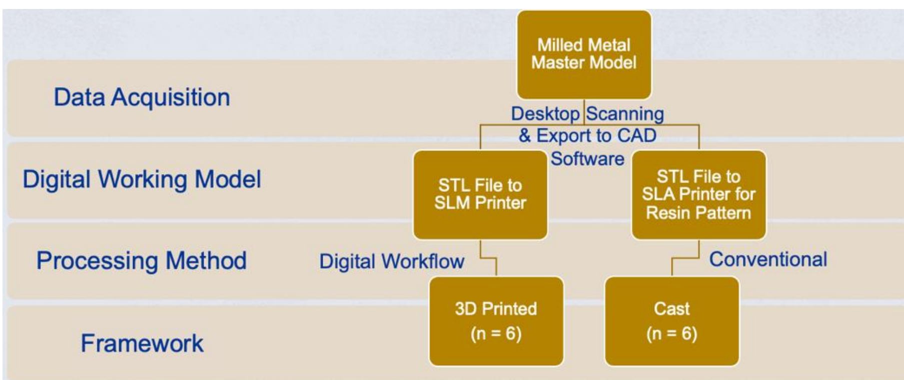

Figure 1 An overview of the methodology

A mandibular partially edentulous metal reference model was fabricated from an acrylic resin typodont model. The typodont model was modified to simulate a Kennedy class I bilateral distal extension with first bicuspid-to-first bicuspid occlusion. The typodont model was first surveyed to determine a common path of insertion and identify undercut areas on the abutment teeth. Surveying is critical to ensuring proper abutment contours, guide planes, and undercuts. The typodont model was then adjusted to accommodate rest seats on the terminal abutments. The final framework design included two occlusal rest seats on the terminal abutment teeth, two circumferential clasps with 0.01-inch undercuts on the mesiobuccal of the terminal abutment teeth, distal guide planes on the terminal abutment teeth, and a lingual plate

5.1 Metal Reference Model

A heavy body polyvinyl siloxane (PVS) impression (Express^{TM}, 3M ESPE) was taken of this typodont model and poured in type IV gypsum (Silky-Rock, Whip Mix Corp) mixed with water according to the manufacturer recommendations in a vacuum mixing machine. The stone model was then scanned using a desktop scanner (D2000; 3Shape) and the generated standard tessellation language (STL) file was exported to a dental laboratory to generate a Co-Cr milled model (Strategy Milling LLC, Pennsylvania). This metal model was used as the reference model to evaluate the fit of all subsequent frameworks (Figure 2). The benefit of using a metal reference model over a stone model was to prevent scratching and distortion during testing, which could skew the results of subsequent trials. The metal reference model was then scanned after spraying using the same desktop scanner (D2000; 3Shape) to generate a digital model. The 3Shape CAD software (Dental System; 3Shape) was then used to virtually survey and design the RPD frameworks according to the previously mentioned design features (Figure 3). The STL files of this digital framework design were used to fabricate all subsequent frameworks.

Figure 2. A cobalt-chromium milled reference model used to evaluate the fit of all RPD frameworks

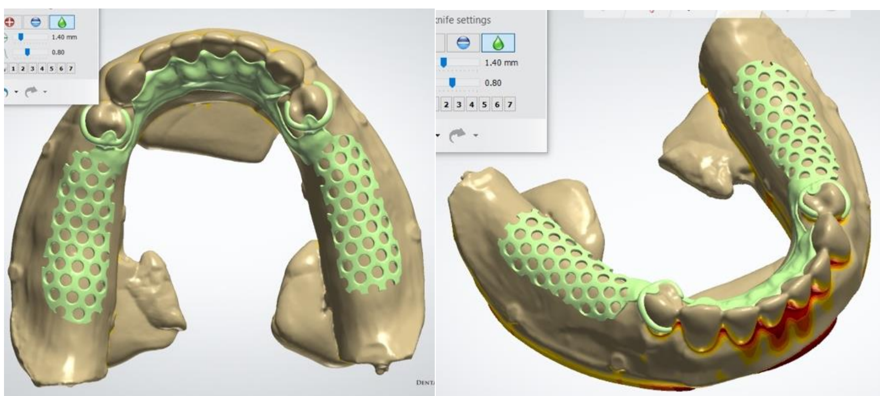

Figure 3 Digital framework designs using 3Shape CAD software

5.2 SLA Cast and SLM Framework

In the combined analog-digital group, the STL files were exported to a 3D resin printer (NextDent® 5100, 3D Systems) to fabricate castable resin patterns (NextDent® Cast, 3D Systems)

(Figure 4A). The 3D printed resin patterns were then sent to a dental laboratory where an experienced dental technician invested and cast the resin patterns in Co-Cr conventionally with an induction centrifugal casting machine (RTG, New York) (Figure 4B). Finishing of all frameworks was completed with aluminum oxide airborne-particle abrasion (sandblasting) and tungsten carbide burs. An electrolyte polishing machine and silicone rubber cup were used for polishing the cameo surfaces.

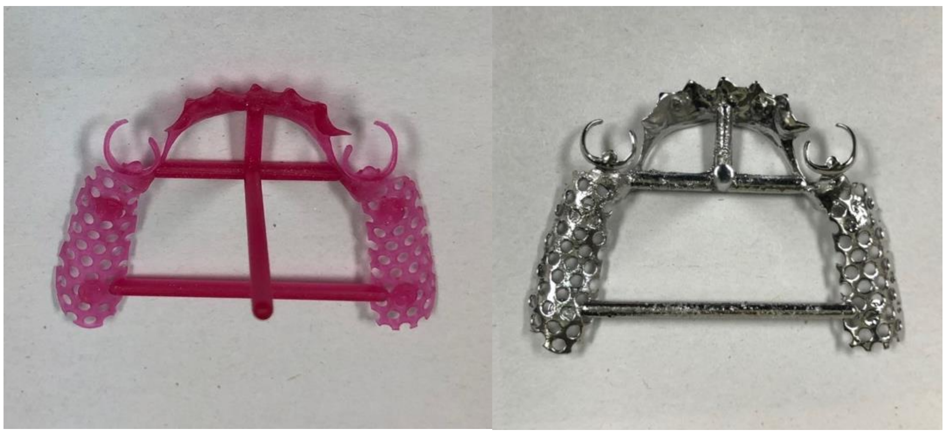

Figure 4A and 4B A) 3D-printed castable resin pattern for the SLA-Cast framework (B) SLA-Cast framework

In the fully digital group, the STL files were exported to a SLM direct metal printing machine (DMP Dental 100, 3D Systems) to print 3D frameworks of the same design using a Co-Cr alloy powder (LaserForm® CoCr, 3D Systems) as recommended by the SLM machine manufacturer (Figure 5). The print layer thickness was set to 20 microns. The build plate orientation was set to 30 degrees. All SLM frameworks were fabricated using the same machine operated by the same experienced operator (J.F.) following the same protocols. These SLM frameworks were finished by sandblasting and diamond burs, then polished by silicone rubber cups in a similar manner to the SLA-Cast frameworks.

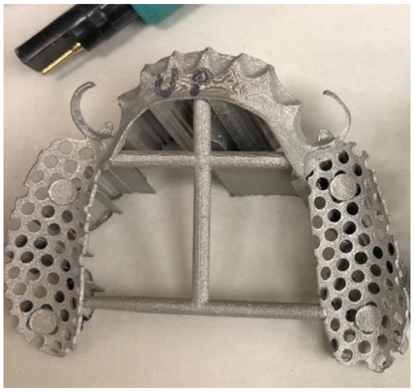

Figure 5 SLM Framework.

5.3 Outcome Measurement

To evaluate the fit of the SLA-Cast and SLM frameworks to the metal reference model, the clinical replica method with silicone impression material and digital calipers was used (Figures 6A and B; Figures 7A and B). Light body PVS impression material (Express^{TM}, 3M ESPE) was injected and evenly painted on the intaglio surfaces of the framework. The RPD framework was then held in place on the reference model with finger pressure that was maintained throughout the setting time determined by the manufacturer. The fit accuracy was evaluated by measuring the vertical thickness of the PVS material at the occlusal rests, midpoint of the retentive circumferential clasp arms, midpoint of the bracing arms, and under the center of the major connector apical to the lateral incisors. The measurements were calculated in micrometers using a calibrated digital caliper (Mitutoyo 500-196-30 AOS Absolute Scale Digital Caliper, Tokyo, Japan). The mean vertical gaps were calculated for each of the four specified sites. Following the protocol delineated by Soltanzadeh et al. and later adopted by Rokhshad et al., a gap from 0 to 50μm was defined as "no perceptible gap," and a gap from 50 to 311μm was defined as a "clinically acceptable gap" (Rokhshad et al., 2022; Soltanzadeh et al., 2019). All gaps greater than 311 μm would, therefore, be deemed clinically unacceptable. All testing and measurements were performed by a single examiner (O.A.) to eliminate potential confounding variables.

Figure 6A and 6B (A) SLA-Cast framework seated on the metal refence model

(B) PVS fit testing of SLA-Cast framework seated on the metal reference model

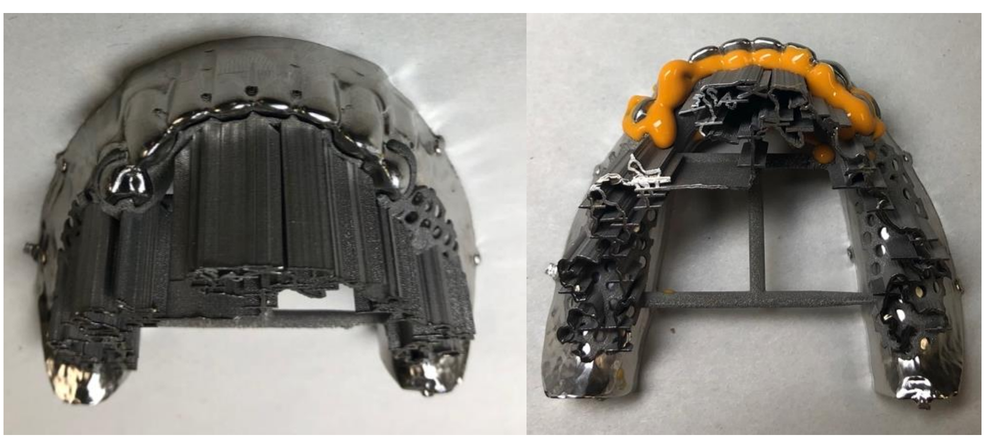

Figure 7A and B A) SLM framework seated on the metal refence model. (untrimmed)

(B) PVS fit testing of SLM framework seated on the metal reference model (untrimmed**)**

The independent *t* test was used for determining the results and statistical analysis between groups (α = 0.05 for all tests). Within each group, all 4 different measured areas were compared using the one-way ANOVA and post hoc Tukey's test. All statistical analysis was done using JASP statistical software by a research statistician from Harvard Medical School (K.Y.).

6.0 Results

The present study was conducted in 2 groups of RPD frameworks made from either castable resin printed patterns (n = 6), or SLM printing (n = 6). A clinically acceptable fit (< 0.311 mm) was achieved at the clasps and rests between the frameworks and the metal reference model, regardless of the production method used. Gap measurements were assessed vertically using PVS impression material and digital calipers at four various sites: occlusal rests, clasp retentive arms, clasp bracing arms, and under the major connector.

The range of overall mean vertical gaps between the frameworks and metal reference model was 0.161 to 0.194 mm for the SLA-Cast frameworks and 0.275 to 0.326 mm for the SLM frameworks. The overall average mean vertical gap between the frameworks and metal reference model was 0.176 mm for the SLA-Cast frameworks and 0.297 mm for the SLM frameworks. This difference in overall average mean vertical gaps is statistically significant ($p < .05$) in the SLA-Cast group versus the SLM group (Table 2).

Method	Overall Mean Vertical Gap +/- Standard Deviation (mm)	p value
SLA-Cast	0.176 +/- 0.014	< .001
SLM	0.297 +/- 0.019	

Table 2 Overall mean vertical gaps between reference model and frameworks

Additional measurements between the frameworks and metal reference model in the areas under the occlusal rests, clasp retentive arms, clasp bracing arms, and major connector are shown in Table 3. The mean vertical gaps measured at each of these areas was significantly different between the two groups (all p values < .05). The best-fitted areas in the SLA-Cast group were the clasp retentive arm (0.071 mm), followed by the occlusal rest (0.097 mm) and clasp bracing arm (0.119 mm), leaving the major connector to be the worst fitted area (0.418 mm). In the SLM group, the clasp bracing arm had the best fit (0.140 mm), followed by the clasp retentive arm (0.232 mm) and occlusal rest (0.302 mm), leaving once again the major connector with the worst fit (0.513 mm). The greatest mean vertical gap discrepancy was found to be under the major connector of the SLM-printed frameworks (0.513 mm).

Framework Component	Mean Vertical Gaps +/- Standard Deviation (mm): SLA-Cast	Mean Vertical Gaps +/- Standard Deviation (mm): SLM	p value
Occlusal rest	0.097 +/- 0.015	0.302 +/- 0.027	< .001
Retentive arm	0.071 +/- 0.012	0.232 +/- 0.028	< .001
Bracing arm	0.119 +/- 0.013	0.140 +/- 0.003	.003
Major connector	0.418 +/- 0.045	0.513 +/- 0.024	.001

Table 3 Comparison of mean vertical gaps under rests, retentive arms, bracing arms, and major connectors for each framework group

One-way ANOVA was used to evaluate the influence of location measured on mean vertical gaps within each group(Tables 4 and 5). For both production methods (SLA-Cast and SLM), the location measured had a significant influence on the fit accuracy ($p < .05$).

SLA-Cast Component	Df	Mean Square	F	p
Location Measured	3	0.159	247.679	< .001

Table 4 One-way ANOVA of the influence of location measured (rest, clasp retentive arm, clasp bracing arm, major connector) on mean vertical gaps within the SLA-Cast group

SLM-Cast Component	Df	Mean Square	F	p
Location Measured	3	0.151	278.837	< .001

Table 5 One-way ANOVA of the influence of location measured (rest, clasp retentive arm, clasp bracing arm, major connector) on mean vertical gaps within the SLM group

Further post hoc comparisons were carried out to determine which locations were significantly different within the SLA-Cast and SLM groups. Within the SLA-Cast frameworks, the major connector fit was significantly different from the fit accuracy at the other locations measured, and the clasp retentive arm fit was also significantly different from that of the bracing arm ($p < .05$) (Table 6). Within the SLM frameworks, the mean vertical gaps at the 4 different locations were all significantly different from each other (Table 7).

SLA-Cast Component Comparison		Mean Difference	Standard Error	ptukey
Rest	Clasp	0.026	0.015	0.317
	BA	-0.022	0.015	0.434
	MC	-0.322	0.015	< .001
Clasp	BA	-0.048	0.015	0.017
	MC	-0.348	0.015	< .001
BA	MC	-0.299	0.015	< .001

Table 6 Post hoc comparison of influence of location measured on mean vertical gaps within the SLA-Cast group**.**

Rest: occlusal rest. Clasp: clasp retentive arm. BA: clasp bracing arm. MC: major connector

SLM Component Comparison		Mean Difference	Standard Error	ptukey
Rest	Clasp	0.070	0.013	< .001
	BA	0.162	0.013	< .001
	MC	-0.210	0.013	< .001
Clasp	BA	0.092	0.013	< .001
	MC	-0.280	0.013	< .001

BA	MC	-0.373	0.013	< .001

Table 7 Post hoc comparison of influence of location measured on mean vertical gaps within the SLM group. Rest: occlusal rest. Clasp: clasp retentive arm. BA: clasp bracing arm. MC: major connector

7.0 Discussion

In the present study, a cast metal reference model was used for testing to avoid introducing measurement inaccuracies caused by abrasion and scratching while the frameworks were manually adapted to the model. All measurements were obtained by a single examiner to avoid possible confounding variables. Finishing and polishing were done to simulate clinical conditions as closely as possible, but several previous studies assessing RPD fit accuracy eliminated the finishing and polishing steps to help reduce human error (Rokhshad et al., 2022; Soltanzadeh et al., 2019). This study tested two different workflows, one involved fabricating a 3D printed resin pattern, which was then cast in a conventional manner using the CLW technique, and the other was fully digital using direct SLM printing. Based on the statistical analyses completed in the present study, the following null hypothesis was rejected: there is no significant difference in the fit accuracy between 3D printed castable resin patterns and SLM-printed frameworks. The null hypothesis that there is no significant difference in fit accuracy among the 4 areas measured under the framework within each group was also rejected. The results from the present study showed that the overall mean vertical gaps of SLM-printed frameworks were significantly greater than those of the SLA-Cast frameworks.

To the author's best knowledge, there exists only 2 current articles in the literature (Arnold et al., 2018; Soltanzadeh et al., 2019) that quantitatively compare the fit accuracy of castable 3D printed resin patterns to SLM-printed frameworks, with the overwhelming majority of articles comparing one or the other to frameworks fabricated by the CLW technique entirely (Bajunaid et al., 2019; Chen et al., 2019; Rokhshad et al., 2022; Tasaka et al., 2020; Tregerman et al., 2019; Ye et al., 2017). Both these articles found that the fit of SLM frameworks was statistically significantly greater than that of RPD frameworks fabricated from castable 3D printed resin patterns, which is in agreement with the results of the present study (Arnold et al., 2018; Soltanzadeh et al., 2019). Arnold et al.'s study used light microscopy to assess fit accuracy and found the difference to be clinically relevant (Arnold et al., 2018). Soltanzadeh et al.'s study used a superimposition software program to assess fit accuracy and concluded that the difference was clinically insignificant (Soltanzadeh et al., 2019). Arnold et al.'s study used a more complex Kennedy class III framework design with more modification spaces than did Soltanzadeh et al.'s study, which may explain some of the differences in their findings (Arnold et al., 2018; Soltanzadeh et al., 2019). In the present study, a clinical replica method using PVS impression material and digital calipers was used to assess fit accuracy between Kennedy class I SLA-Cast and SLM frameworks. Despite reported concerns with using silicone material – including tearing, locking, distortion and poor seating – a recent *in vitro* study found no significant mean differences in the fit assessment among SLM-printed RPD frameworks analyzed through the clinical replica or digital methods (Alabdullah et al., 2022).

Based on the statistical analyses completed in the present study, the following null hypothesis was rejected: there is no significant difference in the fit accuracy between 3D printed castable resin patterns and SLM-printed frameworks. The null hypothesis that there is no significant difference in fit accuracy among the 4 areas measured under the framework within each group was also rejected. The results from the present study showed that the overall mean vertical gaps of SLM-printed frameworks were significantly greater than SLA-Cast frameworks, which corroborates the findings of previous studies, suggesting that challenges may still exist for SLM printing of complex frameworks (Arnold et al., 2018; Soltanzadeh et al., 2019). Soltanzedeh et al. used a digital assessment method incorporating color mapping and comprehensive metrology software to compare the fit accuracy of 3D printed and conventionally cast frameworks fabricated from either dental stone or castable resin-printed models (Soltanzadeh et al., 2019). Their study also found that the 3D printed frameworks had significantly worse fit, but both methods of fabrication still achieved clinically acceptable adaptation (Soltanzadeh et al., 2019). Using light microscopy, Arnold et al. also confirmed a significantly greater misfit with direct RP frameworks versus indirect RP frameworks made from castable 3D printed resin patters (Arnold et al., 2018).

Although the difference in the overall mean gaps between SLA-Cast and SLM frameworks in the present study was statistically significant, it was only 0.12 mm of a difference, which may have no clinical significance because the oral mucosa and soft tissues have a degree of flexibility and can displace under pressure. According to Lytle's historic article, soft tissues can depress up to 300 microns under distal extension RPDs, suggesting that high accuracy may not be as critical in edentulous areas (Lytle, 1962). Nonetheless, the greater the framework deviations, the greater the soft tissue deformation and risk of patient discomfort and soft tissue trauma.

When comparing the mean gap measurements of the SLA-Cast frameworks in the present study to those reported in previous studies in the literature, the present study showed consistency in the fabrication and fit of SLA-Cast frameworks (Arnold et al., 2018; Soltanzadeh et al., 2019). The present study had a narrower range for the overall mean vertical gaps for SLA-Cast frameworks than did Arnold et al.'s study, which was reported to be 0.037 to 0.216 mm (Arnold et al., 2018). The range of overall mean vertical gaps for SLA-Cast frameworks in this study was shown to be 0.161-0.194 mm. The overall mean vertical gap of SLA-Cast frameworks reported in the present study (0.176 mm) was, however, greater than that reported in the literature for other castable 3D printed resin patterns, as well as for conventionally cast frameworks (Arnold et al., 2018; Rokhshad et al., 2022; Soltanzadeh et al., 2019). Rokhshad et al. theorized that the lower accuracy of resin printed cast frameworks – which in their study was an insignificant 6 microns difference in mean gap from conventionally cast frameworks – may be related to inaccuracies during the printing procedure, resin shrinkage in the manufacturing process, or the post-manufacturing process (Rokhshad et al., 2022). This finding suggests that a workflow that transitions between an analog and digital pathways may introduce more compound errors than a fully conventional method when a castable 3D printed resin pattern is involved.

When comparing the results for the SLM-printed frameworks, the present study achieved an overall mean vertical gap that fell within the wide range of SLM framework fit accuracies reported in the literature (Arnold et al., 2018; Bajunaid et al., 2019; Chen et al., 2019; Soltanzadeh et al., 2019). The overall mean vertical gap of SLM-printed frameworks reported in the present study (0.297 mm) was close to that reported in Chen et al.'s study (0.29 mm), but much greater than that reported by more recent studies by Bajunaid et al. and Soltanzadeh et al. and (0.173 mm; 0.15 mm), suggesting that there was less accuracy in the fabrication of our SLM frameworks than there has been in previous studies (Bajunaid et al., 2019; Chen et al., 2019; Soltanzadeh et al., 2019). The overall fit accuracy of the SLM frameworks was, however, less than that reported in older articles (0.363 mm), suggesting that direct SLM printing technology has improved (Arnold et al., 2018). The range of overall mean vertical gaps for the SLM frameworks in the present study was 0. 275 to 0.326 mm, which is narrower than that reported by Arnold et al. (0.109-0.539 mm), suggesting consistency of SLM-printing despite lack of accuracy (Arnold et al., 2018).

In the present study, gaps were measured under the rests, clasp retentive arms, clasp reciprocal arms, and major connectors – all locations important for the biomechanical fit of RPDs. One-way ANOVA testing showed that the fit accuracy as measured by mean vertical gaps was significantly influenced by the location where the vertical gap was measured under the framework within each group. Further post hoc comparisons revealed that within the SLM frameworks, all fit accuracies measured at the different locations were significantly different from one another. However, within the SLA-Cast frameworks, the fit accuracies of the rest seats to the clasp components were not significantly different, suggesting that there was greater consistency in the adaptation of the SLA-Cast frameworks than there was for the SLM frameworks in this study. This may be related to the parameter settings of the SLM printing. The angle of the object placement, build plate orientation, laser spot size, laser scan path and velocity, powder-bed depth, and design of the support struts may influence printing accuracy (Chen et al., 2019). Using stochastic laser path planning, higher scan velocity, smaller laser spot size, and smaller powder-bed depth, for example, may help improve SLM printing accuracy (Chen et al., 2019).

Nonetheless, a clinically acceptable fit (< 0.311 mm) was observed under the retentive and bracing arms of the clasp, as well as under the rest seats, regardless of the framework fabrication method used. Both fabrication methods, however, produced a clinically unacceptable and statistically significant misfit over the major connectors. The greatest discrepancies were observed under the major connectors, which is consistent with the findings of previous studies (Rokhshad et al., 2022; Soltanzadeh et al, 2019). Using color mapping and comprehensive metrology software, Soltanzadeh et al. also found a significant misfit between 3D printed and conventionally cast frameworks (from stone or resin) particularly in the major connector and guide planes, but the method of fabrication in their study did not affect the fit of rest seats or reciprocation plates (Soltanzadeh et al, 2019).

8.0 Limitations

The limitations to this study include only testing one mandibular Kennedy class I design and the use of a silicone material to assess fit accuracy at a limited number of sites. Testing more at-risk design cases, such as Kennedy class III designs with more retainers and clasps, as well as testing cases with various edentulous span lengths, may yield different results. Additionally, the four locations of RPD framework fit that were measured in the present study were predominately around the hard tissues with soft tissue contact only under the lingual plate anteriorly. It is, therefore, difficult to assess whether the distal extension tissue areas are adequately fitted from just the framework evaluation alone.

The present study's method of testing fit accuracy could have also introduced errors in the measurements. All testing and measurements were completed by a single examiner, but the intra-examiner reliability was not calibrated. A recent systematic review on RPD fit accuracy suggests that most studies rely on subjective assessment methods by using either PVS materials, calipers, photographs, or microscopes (Al Mortadi et al., 2020). These techniques, however, may be prone to greater human and material error (Alabdullah et al., 2022; Soltanzadeh et al., 2019). Reported concerns with the clinical replica method using digital calipers to measure PVS thickness include resolution of the digital calipers, framework locking, tearing of thin silicone layers, and poor seating due to the inherent thickness of silicone pastes, which occupy space that would otherwise be essential for complete adaptation (Alabdullah et al., 2022; Soltanzadeh et al., 2019). Due to the elasticity of silicone materials, measurements obtained with digital calipers can also be highly variable depending on the amount of force exerted by the examiner (Alabdullah et al., 2022). Other studies have also reported questionnaires and visual analysis methods as highly prone to inaccuracies (Soltanzadeh et al., 2019). Digital methods of fit assessment can also be affected by scanner resolution (Alabdullah et al., 2022).

Another potential source of error in this study was the outsourcing to various dental laboratories for framework fabrication. The dental laboratory that was used to invest, cast, finish and polish the SLA-Cast frameworks was not the same facility that was used to print, finish, and polish the SLM frameworks due to the equipment limitations of the former dental laboratory. Having one laboratory fabricate the SLA-Cast frameworks and another fabricate the SLM frameworks could have introduced discrepancies in the finishing and polishing components of the methodology that could translate to differences in fit accuracy. Excessive finishing, for example, may cause unnecessary removal of metal from the intaglio surface, causing unintentional gaps (Bajunaid et al., 2019).

9.0 Future Studies

The present study used the 3Shape CAD software for designing RPD frameworks, but several other software programs are available, including Free-Form, ExoCad, Dental wings (DWOS), and Digistell (Rokhshad et al., 2022). As our digital designing and manufacturing techniques become more advanced and efficient, the versatility of materials used for RPD frameworks will continue to grow. All RPDs in the present study were made from Co-Cr alloys, but other materials are also being tested in the digital workflow, including titanium, titanium alloy, polyetheretherketone (PEEK), and ceramic-reinforced PEEK (Bilgin et al., 2016; Jones et al., 2010; Negm et al., 2019; Rokhshad et al., 2022). According to a recent systematic review, the material used for RPD framework fabrication can influence fit accuracy (Carneiro et al., 2021). Some studies suggest that PEEK shows better internal fit than traditionally cast metal RPD frameworks (Carneiro et al., 2021; Ye et al., 2018). Future studies should evaluate different materials using different software design programs. Applying more non-subjective quantitative methods of fit accuracy assessment will reveal just how practical these new materials and manufacturing methods are.

Future studies should also standardize a quantitative assessment for RPD fit accuracy and focus on using software programs that can digitally superimpose all scans to assess the fit accuracy more objectively. This will allow for greater cross-study comparisons in high-yield systematic reviews and meta-analyses to power our evidence-based practices when it comes to digitally designed and manufactured RPD frameworks.

10.0 Conclusions

Within the limitations of this in vitro study, the following conclusions were drawn:

(1) Although there was a statistically significant difference in the fit accuracy of castable 3D-printed resin patterns and SLM-printed frameworks, both frameworks demonstrated clinically acceptable fit accuracy in the clasps and rest seats.

(2) The 0.12-mm difference in overall mean vertical gaps between SLA-Cast and SLM-frameworks may have no clinical significance because the oral resiliency of the soft tissues.

(3) The greatest discrepancy in fit accuracy was observed under the major connector, which was significantly different from all other locations measured in both fabrication methods.

(4) There is room for improvement in the adaptation of RPD frameworks fabricated through a digital workflow.

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