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RESEARCH AND EDUCATION

Adaptation of removable partial denture frameworks fabricated by selective laser melting

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ABSTRACT

Statement of problem. Selective laser melting (SLM) is a novel 3-dimensional (3D) printing technology that can directly form the metal frameworks of removable partial dentures. The adaptation of SLM frameworks has not been thoroughly evaluated.

Purpose. The purpose of this in vitro study was to evaluate the tissue surface adaptation of removable partial denture frameworks fabricated by an SLM technique.

Material and methods. Four types of maxillary partial edentulous resin models were custom made: bilateral second premolars and molars missing, bilateral premolars and first molars missing, all teeth missing except 2 canines, and 2 central incisors missing. According to these dentition-defect patterns, 4 types (I, II, III, and IV) of virtual removable partial denture frameworks were designed, and an SLM printer was used for 3D printing using cobalt-chromium (Co-Cr) alloys (repeated 3 times). As a control, refractory casts duplicated from the resin models were used to fabricate denture frameworks by the lost-wax casting technique. Average gaps and maximum gaps between frameworks and models were measured using the silicone impression material. Two-way ANOVA was used to determine the influence of production methods and design types on the gaps (α=.05).

Results. The 2-way ANOVA showed that average gaps were significantly influenced by the production methods and design types, as well as their interactions (P<.001). With design Types I and II, the average gaps of the SLM-printed frameworks were larger than those of the cast ones (P<.001). However, no such differences were found for design Type III, P=.325, or IV, P=.862.

Conclusions. SLM-printed frameworks achieved an acceptable adaptation. However, among frameworks with a large span and relatively more retainers and clasps, the adaptation of those made by the precision casting technique was slightly better than that of those printed by the SLM technique. (J Prosthet Dent 2019;122:316-24)

Dentition defects are common among elderly people, but the denture restoration rate is rather low.[1-3] Removable partial dentures are suitable prostheses for a variety of dentition defects, with advantages[4] such as minimal tooth preparation, ease of cleaning and repair, and low cost. Removable partial dentures can improve patients' quality of life in a straightforward and effective manner[5] and have a long service life.[6]

Removable partial denture frameworks have been mainly produced by precision casting technology, usually from a nonprecious metal such as a cobalt-chromium (Co-Cr) alloy. The casting shrinkage of Co-Cr alloys is relatively large and requires expansion of the investment materials to compensate.[7]

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Clinical Implications

Among large or complex frameworks, the adaptation of cast frameworks was slightly better than that of SLM-printed ones. For smaller or less complex frameworks, the adaptation of cast and SLM-printed frameworks was comparable. The clinical application of SLM technology will be a trend because of its convenience and improved physical properties.

In addition to the investment material itself, waxes and processing technology also have an impact on casting accuracy.[8,9] Diwan et al[10] measured the adaptation of the cast frameworks for a Kennedy class II dentition defect and found that the gaps between the frameworks and casts were 0.3 to 0.6 mm. Because only a few sites were measured in their experiment, estimating the overall adaptation was difficult. Another disadvantage of casting is the occurrence of defects such as porosity,[11-15] which adversely affects the fracture resistance of the castings.[16]

Three-dimensional printing technology has been used for producing removable partial denture frameworks. In 2003, Witkowski and Lange[17] described making a resin framework using a stereolithography system and then casting it into metal. Williams et al[18] used a computer-aided design (CAD) method to design the 3D shape of a removable partial denture framework and directly printed it by selective laser melting (SLM) technology, reporting a good clinical fit. The manipulative process of SLM technology is straightforward, forming in a single step, and uses minimal material, with good accuracy and excellent mechanical properties.[19-21] The density can be close to 100%.[22-24] Some manufacturers now offer an SLM and laser-sintering apparatus designed for dental laboratory production of removable partial dentures. The accuracy of SLM is affected by factors that include the laser spot diameter, energy density, scanning speed, scanning strategy, and layer thickness.[25,26] Step effect, powder adhesion, slagging, thermal stress accumulation, residual stress, and other inherent constraints of SLM technology may limit its performance.[26-28]

The purpose of this in vitro study was to analyze the adaptation of removable partial denture frameworks with 4 different design types produced by the SLM processing method and compare it with traditional casting. Because the adaptation in this research was indicated by average gaps and maximum gaps, there were a total of 6 null hypotheses: the average gaps of removable partial denture frameworks produced by SLM and casting are equal; the average gaps of removable partial denture frameworks of 4 different designs are equal to each other; there is no interaction between production methods and design types on average gaps; the maximum gaps of removable partial denture frameworks produced by SLM and casting are equal; the maximum gaps of removable partial denture frameworks of 4 different designs are equal to each other; and there is no interaction between production methods and design types on maximum gaps.

MATERIAL AND METHODS

Resin models of 4 maxillary dentition defects were made: bilateral second premolars and molars missing (Kennedy class I defect), bilateral premolars and first molars missing (Kennedy class III defect), all teeth missing except 2 canines (Kennedy class II defect), and 2 central incisors missing (Kennedy class IV defect), as seen in Figure 1A-D. The corresponding clinical removable partial denture frameworks were designed as follows: palatal plate-type connector with 2 clasps (design Type I), combination anterior and posterior palatal strap-type connector with 4 clasps (design Type II), complete palatal connector with no clasps (design Type III), and anterior palatal plate-type connector with 4 clasps (design Type IV), as seen in Figure 1E-H.

The custom maxillary models were scanned using a 3D dental cast scanner (IScan D104i; Imetric 3D SA), and the obtained scan data were exported into the removable denture prosthesis design module (3Shape Dental System 2013; 3Shape A/S). An SLM 3D printing machine (Mlab cusing R; Concept Laser GmbH) was used to complete the 3D printing of the removable partial denture frameworks using Co-Cr alloy powder as the printing material (Fig. 2A, B). The printing powder (remanium star CL; DENTAURUM GmbH & Co KG) of particle size 10 to 30 μm and composition 60.5% cobalt, 28% chromium, 9% tungsten, 1.5% silicon, and <1% other elements such as manganese, nitrogen, niobium, and iron was recommended by the SLM machine manufacturer. The print layer thickness was set to 25 μm, and each designed framework was printed 3 times (n=3).

As a control group, the 4 models were duplicated in gypsum (Snow Rock; Mungyo Gypsum & Engineering Co), and an experienced technician made the cast frameworks (Fig. 2C, D). The casting alloy (Wironit, extra-hard; Bego GmbH & Co. KG) contained 63% cobalt, 30% chromium, 5% molybdenum, 1.1% silicon, and <1% manganese, carbon, nickel, and cadmium. The lost-wax technique, in which a wax pattern of the framework was made from casting wax (GEO Molar clasps; Renfert GmbH), was used. The wax pattern was embedded in a phosphate-bonded investment, which contained no less than 75% silicon dioxide and had about a 0.9% linear expansion rate. For each design, 3 frameworks were cast (Silvercast; Pi dental Fogászati Gyártó Kft) (n=3).

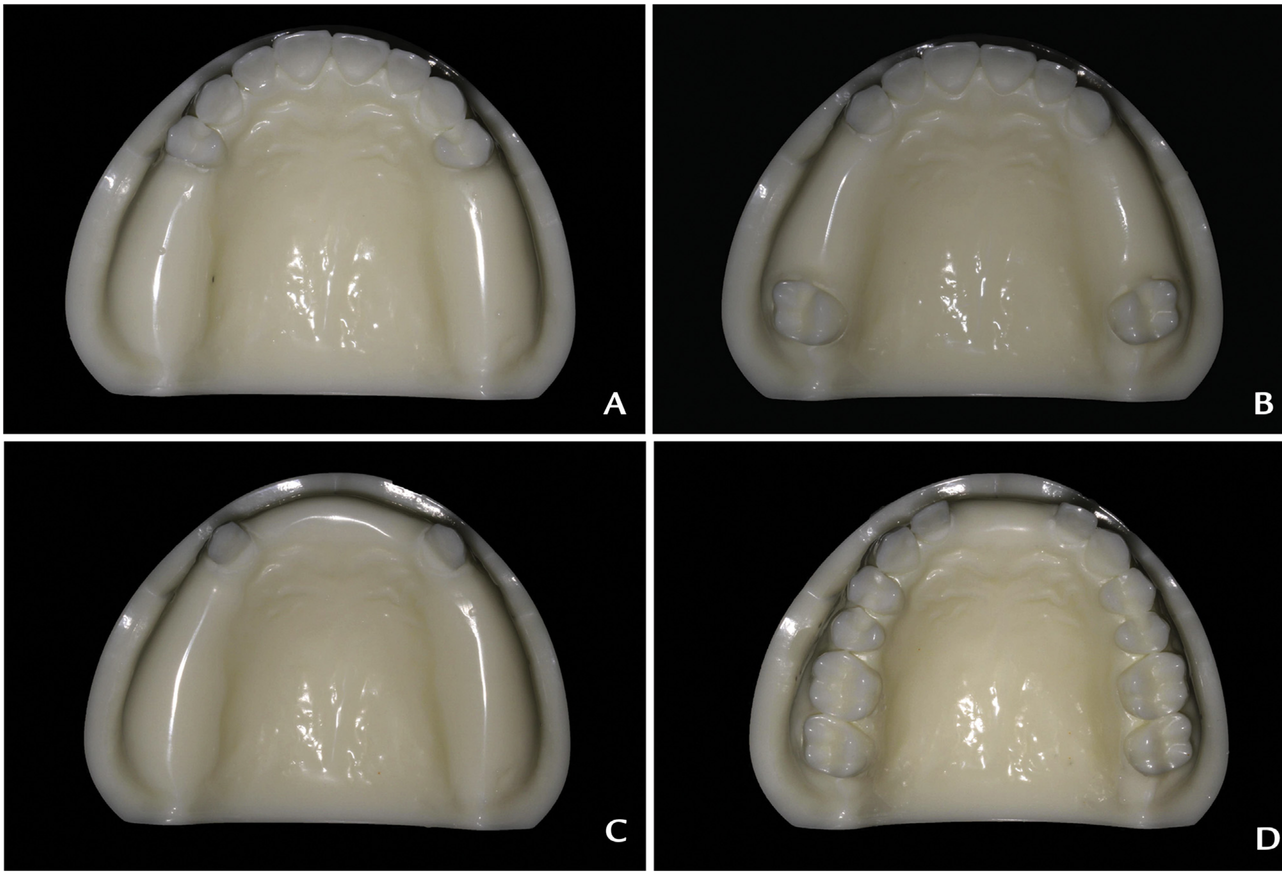

Figure 1. Resin models of four types of maxillary dentition defects with associated digitally designed partial denture framework designs. A, E, Bilateral second premolars and molars missing with palatal plate-type connector and clasps. B, F, Bilateral premolars and first molars missing with combination anterior and posterior palatal strap-type connector and clasps. C, G, All teeth missing except canines with complete palatal connector. D, H, Central incisors missing with anterior palatal plate-type connector and clasps.

All SLM frameworks were fabricated using the same machine, operated by the same experienced operator (X.Z.) following the same protocols. The same batch of printing material was used. The 3D scanning and measuring work was also performed by the same investigator (H.C.) using the same scanner.

Adaptation of the frameworks was measured after manufacture. Tissue surfaces of the SLM-printed and cast frameworks were evenly covered with a polyvinyl siloxane impression material (Variotime Light Flow; Kulzer GmbH) and seated on the corresponding resin models (Fig. 3A). After polymerization of the impression material, the resin models were removed (Fig. 3B), and the frameworks with impression material on them were scanned using the model scanner to obtain the morphology of the impression surface (Fig. 3C). A second scan was made after removing the impression material while maintaining the position of the frameworks to obtain the morphology of the framework tissue surface (Fig. 3D). The scanned data were trimmed using a 3D reverse engineering software program (Geomagic 2012; Geomagic Inc) (Fig. 3E). The mesh data of the impression surface were transformed to a point cloud, and test points were screened (filtered) with a uniform interval of 0.5 mm. Another 3D reverse engineering software program (NX Imageware 13.1; Siemens AG) was used to measure the distances between the impression surfaces and the framework surfaces at the screened test points. The average and maximum distances (gaps) were considered as adaptation criteria (Fig. 3F). A statistical software program (IBM SPSS Statistics, v19.0; IBM Corp) was used for the statistical analysis. Average gaps and maximum gaps were tested by 2-way ANOVA to determine the influence of the framework production methods and design types on the adaptation. Simple effects were analyzed by pairwise comparisons adjusted by the Bonferroni's method (α=.05 for all tests).

RESULTS

A good fit was achieved between the frameworks and corresponding resin models, regardless of the production method, either SLM 3D printing or cast. The mean average gaps between the frameworks and the model

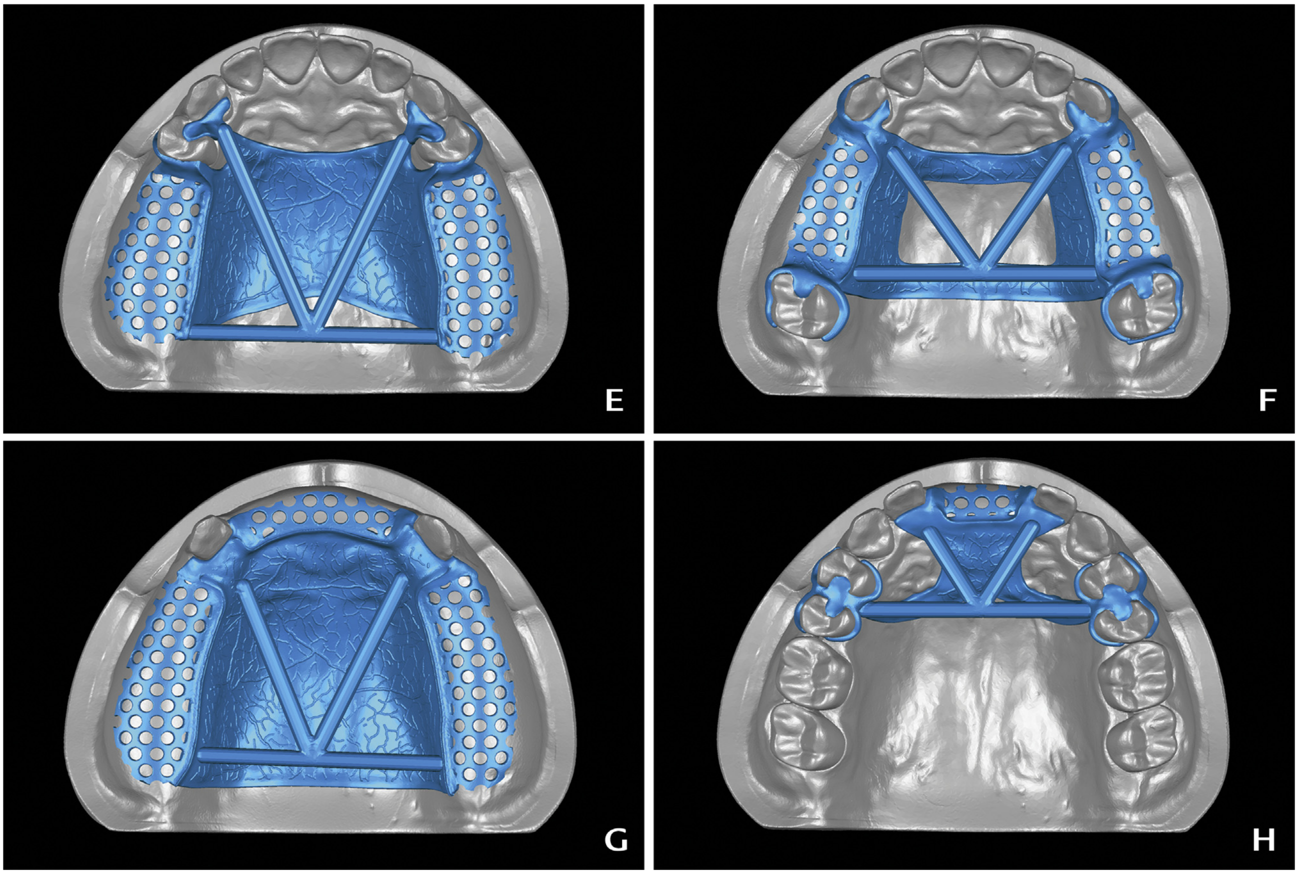

Figure 1. (*continued*). Resin models of four types of maxillary dentition defects with associated digitally designed partial denture framework designs. A, E, Bilateral second premolars and molars missing with palatal plate-type connector and clasps. B, F, Bilateral premolars and first molars missing with combination anterior and posterior palatal strap-type connector and clasps. C, G, All teeth missing except canines with complete palatal connector. D, H, Central incisors missing with anterior palatal plate-type connector and clasps.

surfaces were 0.15 to 0.33 mm for the SLM-printed frameworks and 0.15 to 0.28 mm for the cast frameworks, whereas the maximum gaps were 0.29 to 0.73 mm for the SLM-printed frameworks and 0.32 to 0.63 mm for the cast frameworks (Table 1).

Two-way ANOVA was used to evaluate the influence of the production methods and design types on average and maximum gaps. Both the production method and design type, as well as their interaction, had a significant influence on the average gaps ($P<.001$) (Table 2), whereas only the design type had a significant influence on the maximum gaps (Table 3).

Further pairwise comparisons were carried out based on estimated marginal means and adjustment with the Bonferroni method. First, the average gaps of the cast and SLM-printed frameworks were compared. For design Types I and II, the average gaps of the cast frameworks were smaller than those of the SLM-printed ones. For design Types III and IV, no statistically significant differences were found between the average gaps of the cast frameworks and those of SLM-printed ones (Table 4). The average gaps of the design types were then compared. For the cast frameworks, the average gaps of design Type III were larger than those of the other 3 types (Table 5). For SLM-printed frameworks, the order of the average gaps was design Type II>design Type III>design Type IV, design Type I>design Type IV (Table 5). Finally, the maximum gaps were compared between design types. For SLM-printed frameworks, maximum gaps of design Type IV were smaller than those of the other 3 types (Table 6). For cast frameworks, no significant differences in maximum gaps were found between design types (Table 6). The mean average gaps and mean maximum gaps under different combinations of production method and design type are also illustrated in Figure 4.

DISCUSSION

From the results of 2-way ANOVAs, the following 2 null hypotheses were supported: Maximum gaps of removable partial denture frameworks produced by SLM and casting are equal, and there is no interaction between the production method and design type on maximum

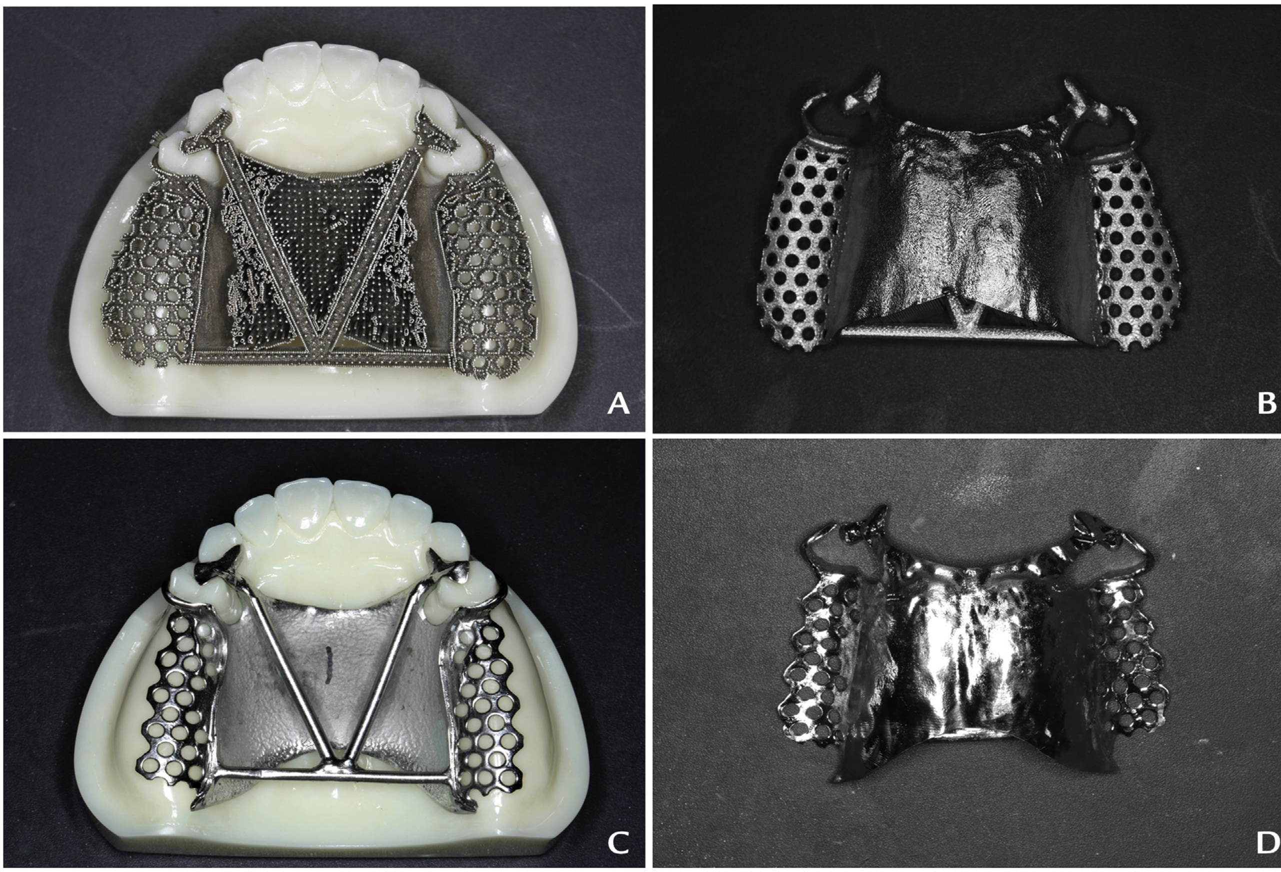

Figure 2. Fabricated removable partial denture frameworks. A, Made by SLM 3D printing. B, Tissue surface of A. C, Made by lost-wax casting. D, Tissue surface of C. SLM, selective laser melting.

gaps. However, the other 4 null hypotheses were rejected: average gaps of removable partial denture frameworks produced by SLM and casting are equal; average gaps of removable partial denture frameworks of 4 different design types are equal to each other; there is no interaction between the production method and design type on average gaps; and maximum gaps of removable partial denture frameworks of 4 different design types are equal to each other. Average gaps were significantly influenced by the production method and design type, whereas maximum gaps were only significantly influenced by the design type. There were interactions of production methods and design types for average gaps, but not for maximum gaps.

In this study, the gaps between the frameworks and model surfaces were measured every 0.5 mm. For each framework, if the measured area of the tissue surface was S, gaps at a total of n test points would be measured by the following equation:

$$n=\frac{S}{l^2}, \tag{1}$$

where l represents the distance between 2 adjacent test points and l was equal to 0.5 mm in this research. The volume of the gap space (V) is approximated to

$$V=\sum_{i=1}^{n} l^2 g_i, \tag{2}$$

where g_i is the gap distance measured at the test point i. Because the average gap ($\overline{g}$) is calculated as

$$\overline{g}=\frac{\sum_{i=1}^{n} g_i}{n}, \tag{3}$$

(1) and (3) substituted into (2) is

$$V=nl^2\overline{g}=s\overline{g},$$

indicating that the average gap is proportional to the gap space volume between the framework and corresponding model tissue surface. Furthermore, the maximum gap represents the ultimate range of deviation of the framework from its oral tissue surface. Thus, average gap and maximum gap are important indexes for evaluating adaptation. If both reach a minimum that is close to zero, good adaptation will be achieved.

Four typical design types of maxillary frameworks were studied: palatal plate-type connector with 2

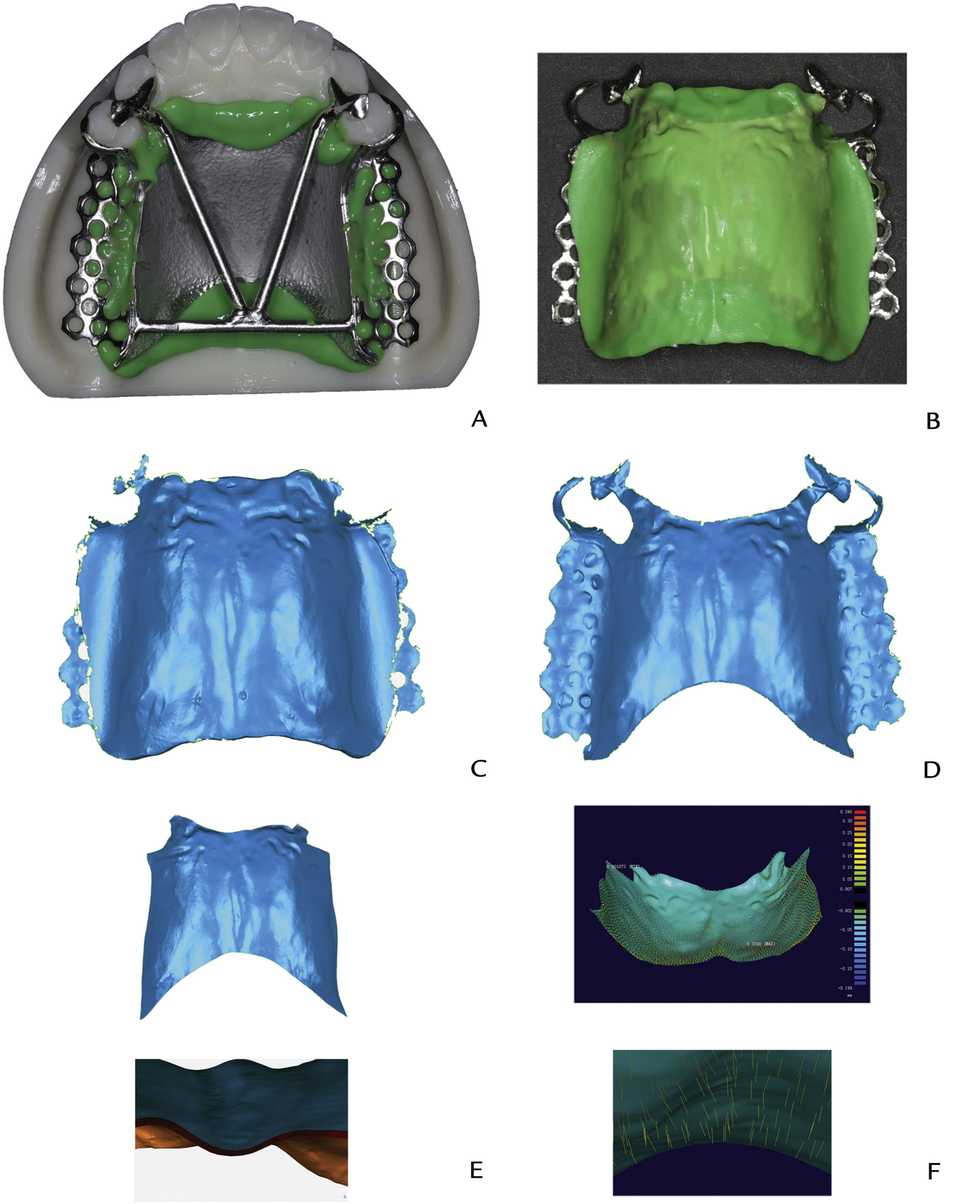

Figure 3. Detection of adaptation of frameworks. A, Frameworks placed on resin models with polyvinyl siloxane impression material. B, Frameworks and impression material remained after revoming resin model. C, Surfaces of impression scanned. D, Tissue surfaces of framework scanned after removing impression material. E, Scanned meshes trimmed in Geomagic software, showing gaps between impression surface and framework surface. F, Distances between points on impression surface and mesh surface of framework measured with Imageware software.

Table 1. Mean average and maximum gaps ±standard error between models and frameworks (mm)

Method	Design	N	Mean Average Gaps ±Standard Error	Mean Maximum Gaps ±Standard Error
Cast	I	3	0.17 ±0.02	0.43 ±0.06
Cast	II	3	0.15 ±0.02	0.49 ±0.07
Cast	III	3	0.28 ±0.02	0.55 ±0.05
Cast	IV	3	0.14 ±0.01	0.44 ±0.06
SLM	I	3	0.29 ±0.02	0.58 ±0.03
SLM	II	3	0.33 ±0.01	0.64 ±0.05
SLM	III	3	0.25 ±0.01	0.59 ±0.05
SLM	IV	3	0.15 ±0.02	0.35 ±0.03

SLM, selective laser melting.

Table 2. Two-way ANOVA of influence of production methods and design types on average gaps

Source	Df	F	P
Method	1	33.880	<.001*
Design	3	19.345	<.001*
Method×design	3	16.115	<.001*

*Mean difference significant (P<.05).

Table 3. Two-way ANOVA of influence of production methods and design types on maximum gaps

Source	Df	F	P
Method	1	2.915	.107
Design	3	4.911	.013*
Method×design	3	2.597	.088

*Mean difference significant (P<.05).

clasps and 2 rests (design Type I), combination anterior and posterior palatal strap-type connector with 4 clasps and 4 rests (design Type II), complete palatal connector with 2 rests (design Type III), and anterior palatal plate-type connector with 4 clasps and 4 rests (design Type IV). The dimensions of these frameworks are listed in the following order: design Type III>design Type I>design Type II>design Type IV. Material contraction may reduce the accuracy. In this experiment, the average gaps of design Type III in cast frameworks were larger than those of the other 3 types, possibly because of its larger dimensions. Clasps and rests, however, had a direct contact with teeth to provide retention or support. Because of the low tolerance for discrepancy, even a slight deviation of the cast clasps or rests may lead to misplacement of the framework, resulting in a large gap between the framework and oral tissue surfaces. The results showed that the average gaps of SLM-printed frameworks were larger than those of cast ones for design Types I and II. Because frameworks in design Types I and II had larger dimensions and relatively more clasps and rests, challenges may exist for SLM to print complex frameworks with larger dimensions and more clasps and rests.

Table 4. Pairwise comparisons of average gap differences among production methods (mm)

Design	(I) Method	(J) Method	Mean Difference ±Standard Error (I-J)	P[a]
I	SLM	Cast	0.12 ±0.02[b]	<.001
II	SLM	Cast	0.18 ±0.02[b]	<.001
III	SLM	Cast	-0.02 ±0.02	.325
IV	SLM	Cast	0.00 ±0.02	.862

SLM, selective laser melting. Based on estimated marginal means, dependent variable = average gap. [a]Adjustment for multiple comparisons: Bonferroni's method. [b]Mean difference significant (P<.05).

Table 5. Pairwise comparisons of average gap differences among design types (mm)

Method	(I) Design	(J) Design	Mean Difference ±Standard Error (I-J)	P[a]
Cast	I	II	0.03 ±0.02	1.000
		III	-0.10 ±0.02[b]	.003
		IV	0.03 ±0.02	1.000
	II	I	-0.03 ±0.02	1.000
		III	-0.13 ±0.02[b]	<.001
		IV	0.01 ±0.02	1.000
	III	I	0.10 ±0.02[b]	.003
		II	0.13 ±0.02[b]	<.001
		IV	0.13 ±0.02[b]	<.001
	IV	I	-0.03 ±0.02	1.000
		II	-0.01 ±0.02	1.000
		III	-0.13 ±0.02[b]	<.001
SLM	I	II	-0.04 ±0.02	.875
		III	0.04 ±0.02	.709
		IV	0.15 ±0.02[b]	<.001
	II	I	0.04 ±0.02	.875
		III	0.08 ±0.02[b]	.035
		IV	0.18 ±0.02[b]	<.001
	III	I	-0.04 ±0.02	.709
		II	-0.08 ±0.02[b]	.035
		IV	0.11 ±0.02[b]	.002
	IV	I	-0.15 ±0.02[b]	<.001
		II	-0.18 ±0.02[b]	<.001
		III	-0.11 ±0.02[b]	.002

SLM, selective laser melting. Based on estimated marginal means, dependent variable = average gap. [a]Adjustment for multiple comparisons: Bonferroni's method. [b]Mean difference significant (P<.05).

Although statistically significant, the difference in the average gaps between SLM frameworks and cast ones was less than 0.2 mm, which may have no clinical significance because human oral mucosa and gingival tissue have a degree of flexibility. After wearing a denture, the soft tissue will cause an appropriate nonuniform deformation to compensate for the gap, even if there are some deviations between the frameworks and dental cast. However, the greater the deviations of the framework, the greater the amount of adaptive nonuniform deformation in the soft tissue. Denture pain will occur when the deformation exceeds the patient's tolerance. In this study, the maximum

Table 6. Pairwise comparisons of maximum gap differences among design types (mm)

Method	(I) Design	(J) Design	Mean Difference ±Standard Error (I-J)	P^a
Cast	I	II	-0.06 ±0.07	1.000
		III	-0.13 ±0.07	.648
		IV	-0.02 ±0.07	1.000
	II	I	0.06 ±0.07	1.000
		III	-0.06 ±0.07	1.000
		IV	0.05 ±0.07	1.000
	III	I	0.13 ±0.07	.648
		II	0.06 ±0.07	1.000
		IV	0.11 ±0.07	.968
	IV	I	0.02 ±0.07	1.000
		II	-0.05 ±0.07	1.000
		III	-0.11 ±0.07	.968
SLM	I	II	-0.06 ±0.07	1.000
		III	-0.01 ±0.07	1.000
		IV	0.24 ±0.07[b]	.035
	II	I	0.06 ±0.07	1.000
		III	0.05 ±0.07	1.000
		IV	0.29 ±0.07[b]	.007
	III	I	0.01 ±0.07	1.000
		II	-0.05 ±0.07	1.000
		IV	0.25 ±0.07[b]	.025
	IV	I	-0.24 ±0.07[b]	.035
		II	-0.29 ±0.07[b]	.007
		III	-0.25 ±0.07[b]	.025

SLM, selective laser melting. Based on estimated marginal means, dependent variable = maximum gap. [a]Adjustment for multiple comparisons: Bonferroni's method. [b]Mean difference significant ($P<.05$).

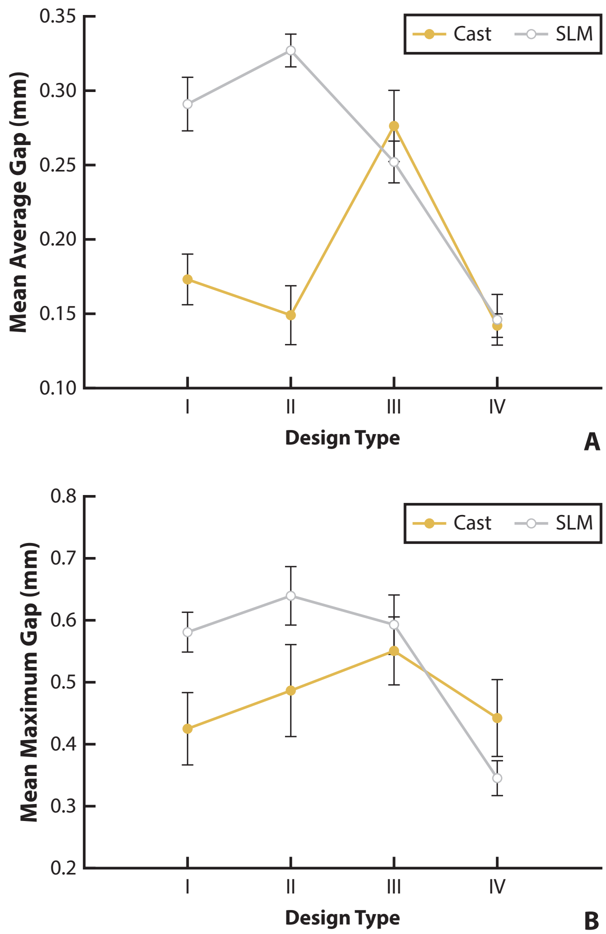

Figure 4. Influence of production methods and design types. A, Mean average gaps. B, Mean maximum gaps. Error bar indicates ±1 standard error. SLM, selective laser melting.

gaps might represent the possible maximum deformation of the soft tissues and might provide an estimate of denture pain. The results showed no statistically significant difference in the maximum gaps between the cast frameworks and SLM-printed ones, so the comfort of the SLM-printed frameworks may be no worse than that of the cast ones.

The setting of each parameter in the SLM printing process has an important influence on accuracy. In particular, the angle of the object placement and the design of the support determine whether the metal powder can effectively overcome gravity during the printing process without collapse. The laser spot size is also important for accuracy in SLM printing. A smaller spot size that is adequate to melt the metal powder can provide higher accuracy than a larger one. Furthermore, the laser scan path and velocity, as well as the powder-bed depth, are all key factors that affect the printing accuracy. Using stochastic path planning and higher scan velocity, accompanied by a smaller powder-bed depth, may help achieve higher accuracy. Future research should optimize object placement, support design, and adjustment of the processing parameters, which may help improve the accuracy and adaptation of the SLM-printed frameworks.

CONCLUSIONS

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

1. The adaptation of SLM-printed frameworks is comparable with that of cast frameworks, except for some large or complex structures.
2. The <0.2-mm difference in the average gaps of cast frameworks and SLM-printed frameworks may have no clinical significance because oral soft tissue has some flexibility.
3. As the parameters of SLM printing were not well optimized in this study, there is room for improvement in the adaptation of SLM-printed frameworks.

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