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Effect of Reinforcement Bar on Trueness of Printed Titanium Kennedy I Removable Partial Denture Frameworks by Selective Laser Melting

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ABSTRACT

Objective: The addition of reinforcement bars is a commonly used method to improve the fabrication trueness of selective laser melting removable partial denture alloy frameworks. However, the effects of different reinforcement bar designs on the trueness of the entire framework remain unclear. This study investigated the trueness of removable partial denture frameworks of pure titanium fabricated by selective laser melting under different reinforcement bar settings.

Method: A virtual framework was designed based on the Kennedy Class I partially edentulous model using computer-aided design software. Frameworks with different reinforcement bar settings (Ti-A without reinforcement bar, Ti-B with a single horizontal bar joining the lingual bar, Ti-C with two more bars at the anterior region, Ti-D with another horizontal bar at the anterior region, and Ti-E with one more bar at the posterior region, $n = 5$) were printed using pure titanium powder using a direct metal laser melting machine. The fabricated frameworks were scanned, and their fabrication trueness was compared with the designed virtual framework using one-way ANOVA.

Results: The overall mean discrepancies for Ti-A, Ti-B, Ti-C, Ti-D, and Ti-E were 0.111, 0.047, 0.073, 0.068, and 0.047 mm, respectively. For the group of Ti-A set with no reinforcement bars, larger discrepancies were observed compared with the other four groups ($P < .05$). Groups Ti-B and Ti-E showed better trueness of the RPI clasps, rests, and distal ends ($P < .05$).

Conclusions: Adding reinforcement bars improved the printing trueness of the pure titanium frameworks, and different settings resulted in various degrees of improvement. Setting a single reinforcement bar to join the lingual bar or an additional reinforcement bar at the distal end significantly enhanced the printing trueness of the RPI clasps, rests, and distal ends.

Introduction

Partial edentulism is a common oral condition encountered in prosthodontics.[1] With the ageing of the population, the incidence of partial edentulism continues to rise, and the demand for restorative treatment is also increasing.[2] Because of the high costs, stringent indications, and necessity of surgical procedures for dental implants, removable partial dentures (RPDs) continue to be an important conventional treatment option for partially edentulous arches, which can directly and effectively improve the quality of life of partial edentulism patients.

Conventionally fabricated RPD involves complex procedures such as (the fabrication of stone casts, evaluation and shape evaluation of the tooth and soft tissues relative to the path of placement, and careful fabrication of the RPD framework using a direct waxing method), which is time-consuming and has been identified as one of the chief complaints of RPD wearers.[3-5] Recently, digital technology has developed rapidly in fabricating frameworks of dental prostheses, including RPDs, with the advantage of shorter production periods, less labour, and discrepancy, and allows for remakes whenever needed.[6-8]

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Selective laser melting (SLM) is a widely used digital technology for fabricating RPD alloy framework.[8-10] SLM produces three-dimensional metal structures directly from a computer-aided designed model, with layers of powder materials that have been melted and layered over each other using a laser. This method allows the creation of complex geometries with concave and thin zones at the base of the metal structure, which is difficult to achieve using subtractive methods. Pure titanium has been frequently selected for SLM-RPD frameworks because of its biocompatibility and lightweight compared with other metals.[11,12] Many studies have confirmed that SLM-RPD frameworks can achieve great clinical outcomes regarding clinical fit, porosity, and surface roughness.[13-16] However, the printing trueness of SLM frameworks is adversely affected by the unpredictable deformation caused by residual stress, which remains an unresolved issue.[8,17] In practice, the effect of residual stress is often reduced by changing the printing angle, adding bottom mesh support, and additional reinforcement bars.[17,18] The setting of additional reinforcement bars varies among dental technicians.[19,20] Several studies have reported the setting of reinforcement bars and their improvement in printing trueness.

This study aims to investigate the influence of different reinforcement bars on the printing trueness of pure titanium frameworks and to explore the optimal settings of reinforcement bars for fabricating pure titanium frameworks by SLM. The null hypothesis was that variations in the reinforcement bar setting would not affect the trueness of SLM pure titanium frameworks.

Materials and methods

Model design

A Kennedy Class I partially edentulous mandibular model was used (Figure 1). Rest seats were prepared on the distal side of the bilateral canines and the mesial of the first premolars. The guide planes were prepared bilaterally on the proximal surfaces of the first premolars. The model cast was then scanned by a 3D scanner (accuracy <10 μm, Shining 3D ExPro, SHINING 3D), and then the virtual framework was designed using computer-aided design software (iPD, Nanjing Profeta Intelligent Technology). A lingual bar was designed as the major connector, and RPI clasps were designed at the bilateral first premolars. Five sets of reinforcement bars (P3DS, Nanjing Profeta Intelligent Technology) were designed (Ti-A, Ti-B, Ti-C, Ti-D, and Ti-E) as shown in Figure 2. Group Ti-A was designed without a reinforcement bar. In contrast, group Ti-B was designed with a single horizontal bar joining the lingual bar. Group Ti-C was designed with two additional bars in the anterior region, and group Ti-D was designed with another horizontal bar in the anterior region. The Ti-E group received an additional bar in the posterior region. The diameter of the reinforcement bar was 2.5 mm, according to previous studies.[19] Five sets ($n = 3$) of reinforcement bars were designed based on the grouping described before. The surface difference in the major connector was expressed as mean $\pm$ standard deviation (SD), as follows: 0.0549 $\pm$ 0.0221, 0.0208 $\pm$ 0.0089, 0.0162 $\pm$ 0.0075, 0.0161 $\pm$ 0.0065, 0.0228 $\pm$ 0.0101. The common SD was calculated based on the SD of each group, resulting in 0.01239. By combining the means and sample sizes of each group, the effect size f was calculated to be 1.17871. Utilizing G*Power software with a Power of 0.90 and α of 0.05, the required sample size for each group was 4 using one-way analysis of variance *F*-tests. Combined with power analysis and references, the sample size was finally determined as 5.[16,17,19]

Framework printing

The frameworks were printed with pure titanium powder (TA1, Jiangsu Vilory Advanced Materials Technology) using a direct metal laser melting machine (IS200, Nanjing Profeta Intelligent Technology). The framework was arranged with the occlusal surfaces of the four rests parallel to the baseplate of the 3D printer, such that the bearing surfaces were set upward.[11] The diameter of the laser beam was 0.065 mm. A scan speed of 1000 mm/s, laser spot diameter of 0.08 to 0.1 mm, and layer thickness of 0.03 mm were used for the SLM framework. Five frameworks were fabricated for each

Fig. 1 – The Kennedy Class I reference model.

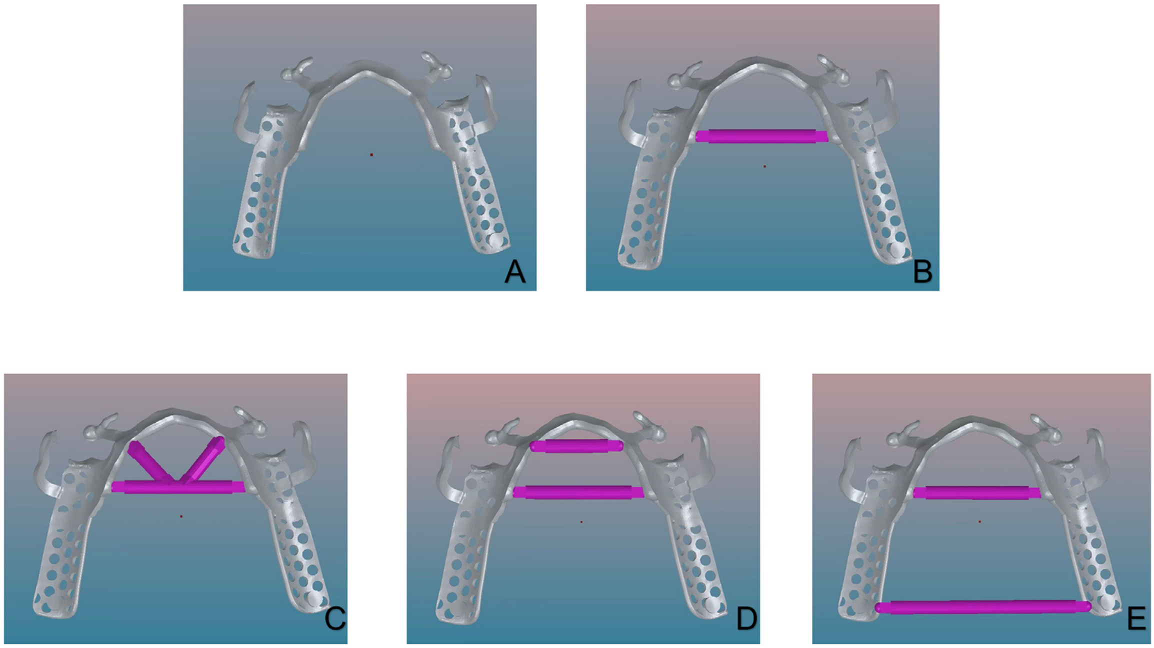

Fig. 2 – Design of RPD frameworks with different reinforcement bars. (A) Ti-A, RPD framework without reinforcement bar. (B) Ti-B, RPD framework with a single bar. (C) Ti-C, framework with 3 bars at the anterior region. (D) Ti-D, framework with two horizontal bars. (E) Ti-E, framework with a bar at the anterior region and a bar at the posterior region.

group (Figure 3). The printed frameworks were annealed at 650°C for 1 hour. After fabrication, the support materials were cut from the platform, and the frameworks were not polished.

Data measurement

The fabricated frameworks were scanned with a laboratory 3D scanner (accuracy 5 μm, D2000, 3Shape A/S), and the 3D data were obtained and exported in the standard tessellation language format. Trueness was verified by superimposing the SLM framework fabrication data on the design data using the best-fit algorithm of the 3D data inspection software (3-matic, Materialise). The surface differences in the major connector (lingual bar), rests, RPI clasps, and distal ends were compared. The reinforcement bar area was excluded from the superimposition or comparison. Thirteen verification sites were selected, as shown in Figure 4, with five sampling points arbitrarily selected at equal intervals at each site. The major connector area included the centre and bilateral joining areas of the lingual bar. Four sites on bilateral mesial and distal rests were included in the rests area. Two sites on RPI clasps, the minor connector, and distal end areas were selected.

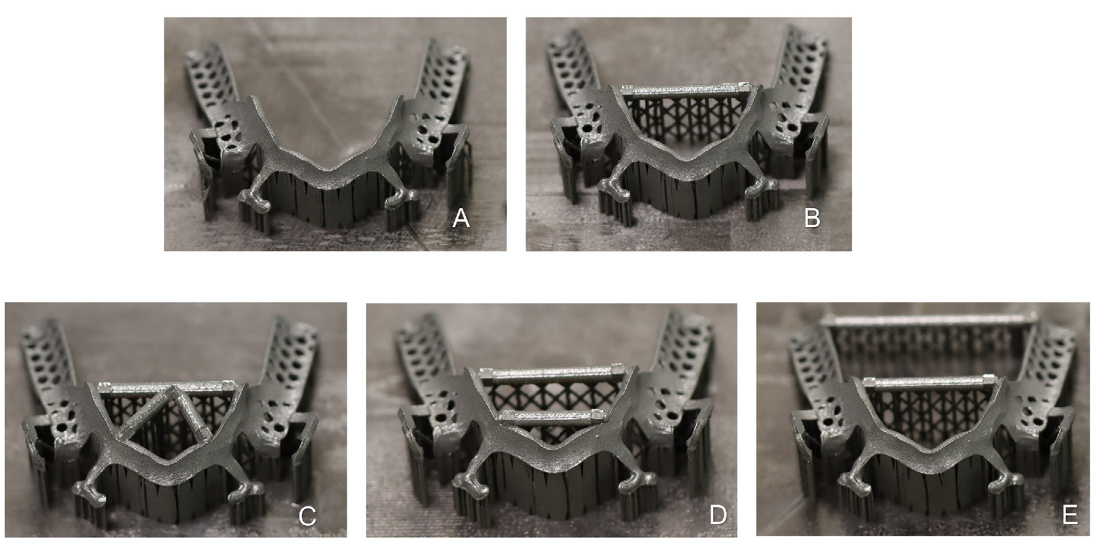

Fig. 3 – The printed frameworks. (A) Ti-A, (B) Ti-B, (C) Ti-C, (D) Ti-D, (E) Ti-E.

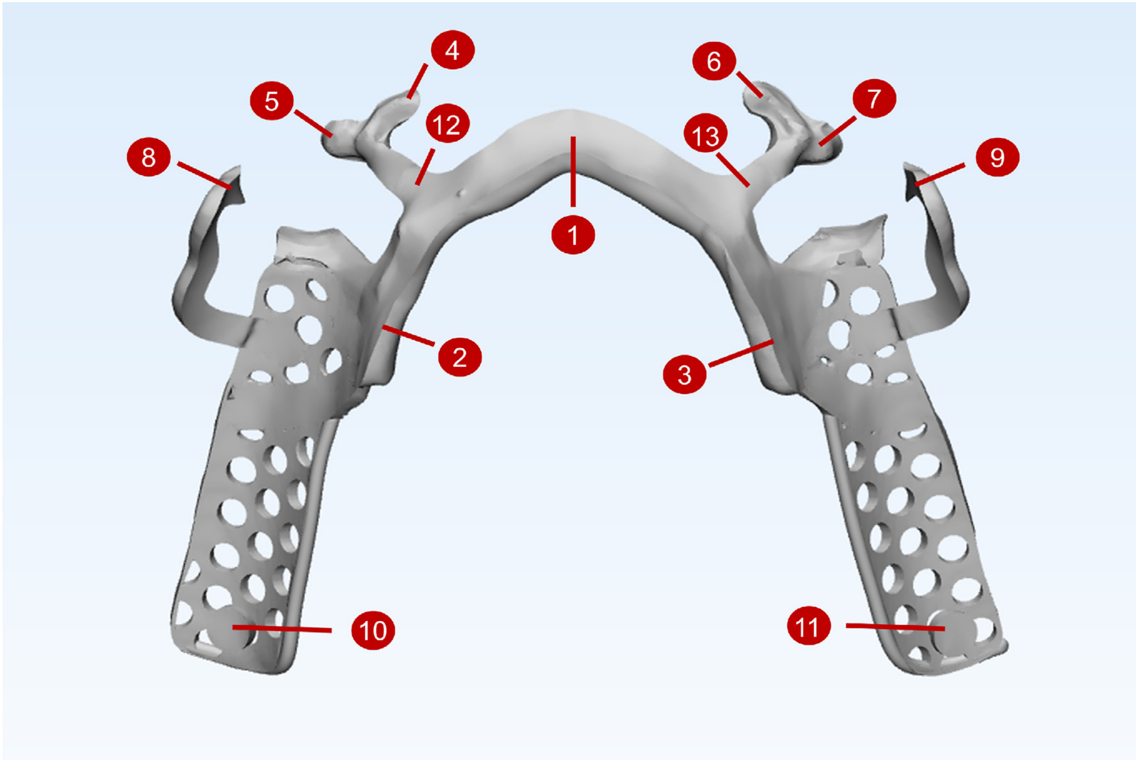

Fig. 4 – Measurement sites for verification. (1) Lingual bar: centre, (2) lingual bar: right-side joining area, (3) lingual bar: left-side joining area, (4) rest on right canine, (5) rest on right first premolar, (6) rest on left canine, (7) rest on left first premolar, (8) clasp: right-side, (9) clasp: left-side, (10) distal end: right-side, (11) distal end: left-side, (12) minor connector: right-side, (13) minor connector: left-side.

Statistical analysis

The data were analysed using a statistical software program (IBM SPSS Statistics, v26.0; IBM Corp.). One-way ANOVA followed by Bonferroni post-hoc test was used to evaluate the settings of reinforcement bars on the fabrication trueness of each area ($\alpha = 0.05$).

Results

The colour maps in Figure 5 illustrate the typical discrepancy between the frameworks aligned with the design data. At the same scale, Ti-A exhibited a broader region of large discrepancy (red or deep blue) than the other groups.

The amount of discrepancy measured at the major connector rests, RPI clasps, distal ends, and minor connectors are shown in Figure 6.

In the major connector area, the mean discrepancies were 0.0560, 0.0203, 0.0170, 0.0172, and 0.0237 mm for Ti-A, Ti-B, Ti-C, Ti-D, and Ti-E, respectively (Figure 6, Table). A smaller discrepancy was observed for the frameworks set with reinforcement bars than those without (group Ti-A), and the values between Ti-B, Ti-C, Ti-D, and Ti-E were not statistically different ($P < .05$). Among all verification sites, the major connector appeared to have the smallest discrepancy.

For the rests area, the mean discrepancies were 0.1399, 0.0690, 0.1051, 0.1034, and 0.0889 mm for Ti-A, Ti-B, Ti-C, Ti-D, and Ti-E, respectively. The Ti-B group set with a single reinforcement bar connected to the lingual bar showed the best fabrication trueness, followed by Ti-E. Adding another reinforcement bar near the major connector of the framework (Ti-C, Ti-D) slightly lowered the fabrication trueness.

The mean discrepancies at the RPI clasps area were 0.1557, 0.0634, 0.1229, 0.0968, and 0.0384 mm for Ti-A, Ti-B, Ti-C, Ti-D, and Ti-E, respectively. The Ti-E group with two reinforcement bars exhibited better fabrication trueness than the other groups. Reducing the reinforcement bars that connected the distal ends of the framework lowered the fabrication trueness of the Ti-B group, whereas adding reinforcement bars near the major connector further lowered the fabrication trueness.

At the distal ends, the mean discrepancies were 0.1696, 0.0554, 0.0960, 0.0952, and 0.0358 mm for Ti-A, Ti-B, Ti-C, Ti-D, and Ti-E, respectively. A greater discrepancy was observed for the frameworks without reinforcement bars. The Ti-E group exhibited greater trueness than the other reinforcement bar designs, followed by the Ti-B group. No significant differences were observed between Ti-C and Ti-D ($P < .05$).

The mean discrepancies in the minor connector area were 0.0350, 0.0205, 0.0185, 0.0182, and 0.0171 mm for Ti-A, Ti-B, Ti-C, Ti-D, and Ti-E, respectively. The Ti-A set with no reinforcement bars exhibited a greater discrepancy than the other groups. No statistically significant differences were observed among Ti-B, Ti-C, Ti-D, and Ti-E ($P < .05$).

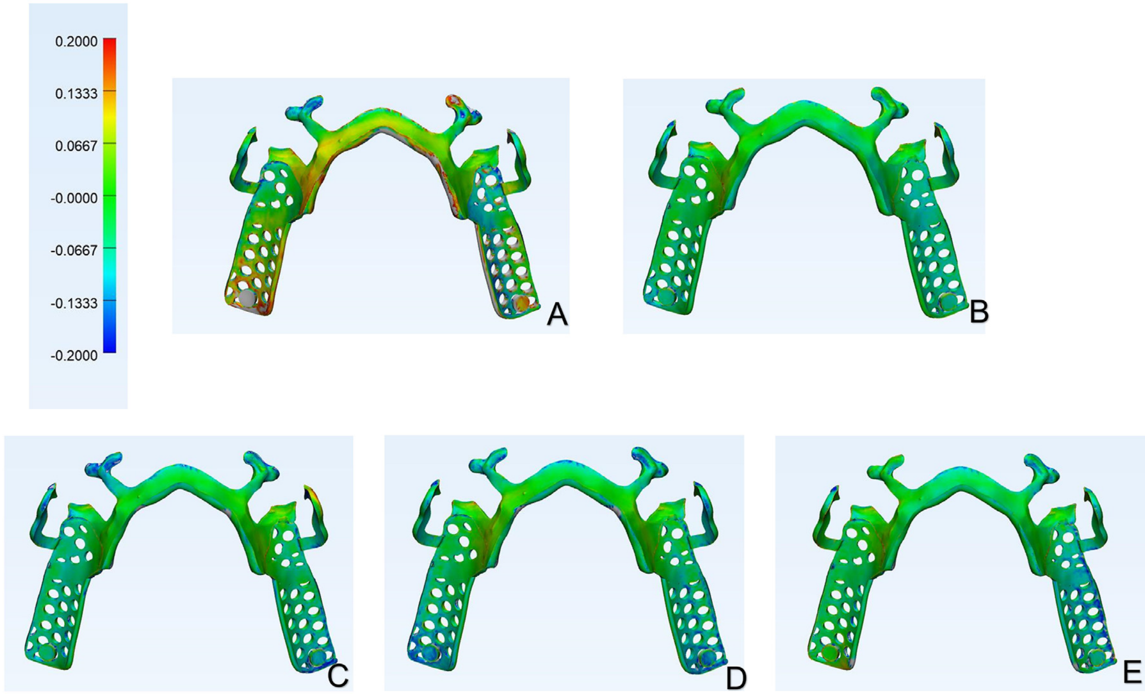

Fig. 5 – Colour maps of shape differences on SLM frameworks set with different reinforcement bars. (A) Ti-A, (B) Ti-B, (C) Ti-C, (D) Ti-D, (E) Ti-E.

Discussion

Among various fabrication methods, SLM is widely used to fabricate metal frameworks. Previous studies have evaluated the fabrication trueness by comparing printed and conventional cast frameworks. The trueness of RPD frameworks has been reported in relation to the specific design, structural components, and printing quality of the metallic parts. Research has also found that setting a reinforcement bar can control the displacement in the central area of the lingual bar.[19] However, no study has yet investigated how the design of different reinforcement bars is associated with the fabrication trueness of SLM frameworks. The present study investigated the printing trueness of SLM pure titanium frameworks

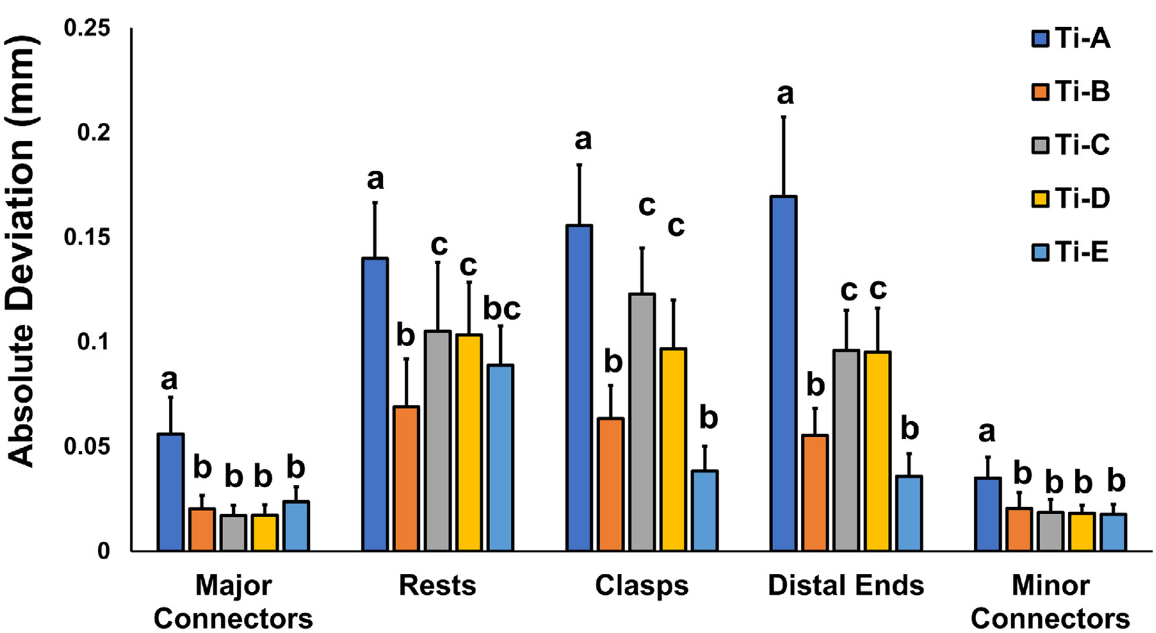

Fig. 6 – Mean values of different groups on SLM frameworks (mm). (A) Major connector, (B) rests, (C) clasps, (D) distal ends, (E) minor connectors. Lowercase letters indicate differences among areas considering same area.

Table – Printing mean ± standard deviation trueness (mm) in each area.

Group	Areas				
	Major connector	Rests	Clasps	Distal ends	Minor connectors
Ti-A	0.0560 ± 0.0176 Ad	0.1399 ± 0.0269 Ac	0.1557 ± 0.0290 Ab	0.1696 ± 0.0379 Aa	0.0350 ± 0.0099 Ae
Ti-B	0.0203 ± 0.0064 BCc	0.0690 ± 0.0229 Da	0.0634 ± 0.0159 Da	0.0554 ± 0.0129 Cb	0.0205 ± 0.0076 Bc
Ti-C	0.0170 ± 0.0050 Cd	0.1051 ± 0.0329 Bb	0.1229 ± 0.0221 Ba	0.0960 ± 0.0192 Bc	0.0185 ± 0.0063 Bd
Ti-D	0.0172 ± 0.0051 Cc	0.1034 ± 0.0252 Ba	0.0968 ± 0.0231 Cb	0.0952 ± 0.0211 Bb	0.0182 ± 0.0039 Bc
Ti-E	0.0237 ± 0.0071 Bc	0.0889 ± 0.0188 Ca	0.0384 ± 0.0120 Eb	0.0358 ± 0.0108 Db	0.0171 ± 0.0048 Bc

Uppercase letters indicate differences among groups considering same area (difference between rows). Lowercase letters indicate difference among areas considering same group (difference between columns).

and compared the fabrication trueness of the frameworks setting with four types of reinforcement bars using 3D data evaluation.

The null hypothesis was rejected, and the different designs of the reinforcement bars affected the fabrication trueness of the SLM pure titanium frameworks. Overall, the setting of the reinforcement bars enhanced the printing trueness of the pure titanium frameworks in different areas, which might mean that the placement of the reinforcement bars was conducive to reducing the deformation caused by residual stress. For the major and minor connector areas, the impact of the different types of reinforcement bars on trueness did not exhibit significant variation among the groups. Compared to other areas, the RPI clasps and rest trueness are more important for retention and stability. In the RPI clasps, rests, and distal ends areas, the Ti-B and Ti-E reinforcement bars demonstrated greater printing trueness than the other two, resulting in a clinically acceptable range.[17,21] In contrast to Ti-B, the additional reinforcement bars near the major connector of Ti-C and Ti-D resulted in a decrease in trueness for the RPI clasps, rest, and distal ends. Moreover, the Ti-E group with reinforcement bars in the posterior region may have contributed specifically to the enhanced trueness at the distal ends. The placement of reinforcement bars in the framework fabrication process can effectively mitigate deformation and enhance trueness. Notably, setting a single bar at the joining areas between the major connectors or two separate bars improved the printing trueness.

In each group, the major and minor connectors exhibited superior printing trueness. This may have been affected by matching algorithms. The matching algorithm is based on the minimum root mean square error, which means that the part with a large area and the part close to the centre may show a smaller deviation.[22] Therefore, when comparing the printing trueness of different areas within the same group, the results need to be interpreted in a limited manner. Moreover, manual selection of points may be a potential source of error. To reduce this impact, a specialized operator blinded to the groups was assigned to perform the selection. Another limitation of this study is that it included only one model, a Kennedy Class I partially edentulous mandibular model. More typical models and designs, including maxillary partial edentulism models, should be investigated in greater detail. Further research is required to clarify the underlying impact of the settings of the enhancement bars on the printed metal parts during the fabrication process.

Conclusions

For the typical Kennedy Class I partially edentulous model, different settings of the reinforcement bars enhanced the printing trueness of the SLM pure titanium frameworks, and setting a single reinforcement bar at the joining areas between the major connector or two separate bars was more effective.

Author contributions

Li Zhang and Yingjie Yi were responsible for studying concepts and design, quality control, and revising the manuscript critically for important intellectual content. Ling Ding and Jiali Meng contributed to the drafting of the manuscript. Guofeng Wu conceived the manuscript, contributed to the analysis plan and interpretations, and contributed to the formal data analysis. All listed authors meet the requirements for authorship, and they both read and approved the final manuscript.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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