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# Effect of different tooth preparation designs on the marginal and internal fit discrepancies of cobalt-chromium crowns produced by computer-aided designing and selective laser melting processes

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**PURPOSE.** To evaluate the impact of five different tooth preparation designs on the marginal and internal fit discrepancies of cobalt-chromium (CoCr) crowns produced by computer-aided designing (CAD) and selective laser melting (SLM) processes. **MATERIALS AND METHODS.** Five preparation data were constructed, after which design crowns were obtained. Actual crowns were fabricated using an SLM process. After the data of actual crowns were obtained with structural light scanning, intaglio surfaces of the design crown and actual crown were virtually superimposed on the preparation. The fit-discrepancies were displayed with colors, while the root means square was calculated and analyzed with one-way analysis of variance (ANOVA), Tukey's test or Kruskal-Wallis test ($\alpha$ = .05). **RESULTS.** The marginal or internal color-coded images in the five design groups were not identical. The shoulder-lip and sharp line angle groups in the CAD or SLM process had larger marginal or internal fit discrepancies compared to other groups ($P < .05$). In the CAD process, the mean marginal and internal fit discrepancies were 10.0 to 24.2 µm and 29.6 to 31.4 µm, respectively. After the CAD and SLM processes, the mean marginal and internal fit discrepancies were 18.4 to 40.9 µm and 39.1 to 47.1 µm, respectively. The SLM process itself resulted in a positive increase of the marginal (6.0 - 16.7 µm) and internal (9.0 - 15.7 µm) fit discrepancies. **CONCLUSION.** The CAD and SLM processes affected the fit of CoCr crowns and varied based on the preparation designs. Typically, the shoulder-lip and sharp line angle designs had a more significant effect on crown fit. However, the differences between the design groups were relatively small, especially when compared to fit discrepancies observed clinically. [J Adv Prosthodont 2021;13:333-42]

**KEYWORDS**
Fit discrepancies; Cobalt-chromium crown; Computer-aided design; Selective laser melting; Tooth preparation design

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## INTRODUCTION

Previously, cobalt-chromium (CoCr) ceramic restorations were mainly made with the lost-wax casting (equivalent manufacturing) technique, which is a complex procedure that includes distortion of wax patterns, irregularities in the cast metal, and time-consuming processing.[1] Over recent years, the computer-aided design (CAD)-based selective laser melting (SLM) (additive manufacturing) technique has been applied to produce dental metal restorations. The SLM technology can create products based on the sliced data from a digital design; it can construct the objects layer by layer by selectively melting metal powder with laser or electron beams.[2] In theory, this technique can be used for any restoration with a complex structure. Recent studies have found that SLM CoCr ceramic restorations could achieve satisfactory fit[3,4] and excellent mechanical[5] and chemical properties.[6,7]

The fit of restorations is considered a key indicator affecting the longevity of dental restorations.[8-10] Unlike the traditional casting technique, modern dental workflow combines CAD and computer-aided manufacturing (CAM) steps to make the restoration. Before the CAM step, open access systems allow data to be captured from various sources (such as intraoral scanner or model scanner)[11] and then use professional dental software to design the restoration. Scholars believe that the open systems may have the advantage of increasing the accuracy and reproducibility of the final all-ceramic restorations.[12] Previous studies on the fabrication procedure of all-ceramic restorations with computer numeric controlled (CNC) milling revealed that although the products of digital dental workflows were prone to imprecisions, differences between CAD and actually milled restorations were small, especially when comparing typical fit discrepancies clinically observed.[13] Similarly, the production of CoCr restorations with SLM technology includes two processes: CAD and SLM. Numerous previous studies[14-17] evaluated the effect of SLM technology on the marginal and internal fit of final CoCr alloy restorations. However, to date, the effect of each step (such as CAD and SLM processes) in the digitized dental workflows on the marginal and internal fit of SLM CoCr crowns has not been reported.

Adhering to the tooth preparation design principle in clinical practice is essential; otherwise, the fit of dental restorations may be significantly affected.[18-20] An early review focused on the influence of physical requirements of tooth preparation such as shoulder width, emergence profile, and shoulder angle on dental pulp. It also considered the teaching of metal ceramic crown preparation, the failure of metal ceramic crowns, and the influence that preparation quality had on these failures.[18] A recent study[21] has revealed that the finish line type did not influence the internal gap between copings and dies, whereas the SLM-fabricated CoCr copings on teeth prepared with a deep chamfer finish line had the lowest marginal gap. In practice, dentists tend to overlook certain details (such as finish line design and smooth surfaces); however, it remains unknown to what extent this affects the fit of CAD and SLM processes in the digital dental workflows of SLM CoCr crowns.

Therefore, in this study, we evaluated the effect of CAD and SLM processes in the SLM technique on the marginal and internal fit of CoCr crowns with five different tooth preparation designs after verification in the Geomagic Studio software. Herein, we hypothesized that the five different tooth preparation designs would have the same effect on the marginal and internal fit of CoCr crowns produced by CAD and SLM processes.

## MATERIALS AND METHODS

An ideal crown preparation, which was designed by the Imageware software (NX Imageware13.2, Electronic Data Systems (EDS) Co., Vermont, CA, USA) had the following specifications: a smooth, 1.0 mm heavy chamfer finish line that follows a distinct and continuous finish line void of spikes and lips, 6 degrees combined convergence angle, a functional cusp bevel, 1.5 to 2 mm of occlusal reduction, 1.2 to 1.5 mm of axial reduction and an overall rounded and smooth surface.[20] Then, as previously described,[20,22,23] four different marginal forms and one internal line angle were reconstructed; only the marginal forms or internal line angle of each constructed tooth preparation were modified, while the remaining parts of the preparation remained unchanged (morphologically). Five reference tooth preparation data, heavy chamfer finish line (chamfer), 135° finish line (135°), feather-edge finish line (feather), 0.5 mm 90°shoulder and 0.5 mm lipped finish line (shoulder-lip), and the heavy chamfer finish line and sharp line angle of internal surfaces (sharp line angles) (Fig. 1), were obtained. Each reference preparation was divided into two parts: marginal (1.0 mm from the edge of the tooth preparation) and internal area, with Studio software (Studio Wrap 2015, Geomagic GmbH, Stuttgart, Germany), and saved as STL files for later use.

Then, five reference preparations were imported into a professional dental design software (Dental System, 3Shape A/S, Copenhagen, Denmark), with ten design crowns (n = 10) for each group. As advised by Dental System, the parameters were designed as follows: margin line offset: 0.15 mm; offset angle: 65°; extension offset: 0.15 mm; minimum thickness: 0.50 mm; extra cement gap (internal gap): 50 µm; cement gap (marginal gap): 30 µm; distance to margin line: 1.0 mm; smooth distance: 0.20 mm. Finally, the design crowns of each group were numbered from 1 to 10 by group (the crown samples of each group were matched one by one in the follow-up experiment) and saved as STL files for subsequent use.

The design crown data of each group were sent to an SLM machine equipped with fiber laser (Concept laser Mlab, Concept Laser GmbH, Lichtenfels, Germany). Then, crown designs for each group were printed according to the manufacturer's recommendation under nitrogen protection with 10 to 45 µm diameter CoCr powder (CT-AB-CoCr-D, Zhongkekang Titanium Material Technology Co. Ltd., Fujian, China) as the raw material. The production parameters were as follows: the intaglio surface of the crown was placed upward, and perpendicular to the plane of a tectonic plate; the Yb:YAG fiber laser machine was set at 100 W, the focus diameter was 50 µm, the wavelength was 1,070 nm, and the laser cladding thickness was 25 µm. After the crown was formed, heat treatment was applied in a burn-out furnace (N 41/H, Nabertherm GmbH, Lilienthal/Bremen, Germany). According to the manufacturer of the CoCr powder, the heat treatment procedure was set as follows: the furnace was heated from room temperature to 960°C under the protection of argon for 4 h and cooled to room temperature after being kept at 960°C for 1 h. Subsequently, the wire cutter was used to remove the supporting structure. Finally, the actual CoCr crowns were obtained for each design group (n = 10 per group).

According to the manufacturer's instructions, the lab scanner (E4, 3Shape A/S, Copenhagen, Denmark) with a scanning accuracy of 4 µm (ISO), high speed,

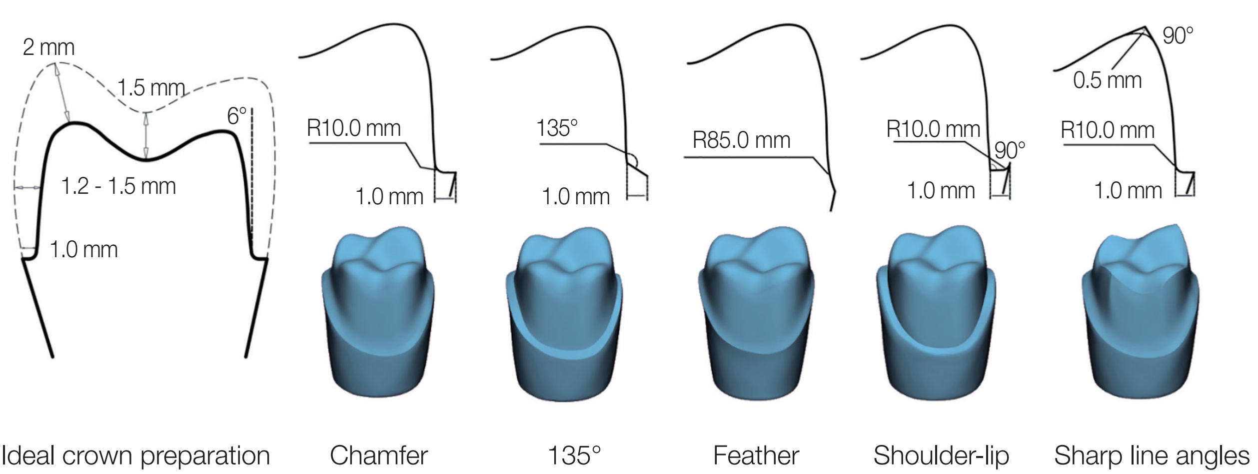


**Fig. 1.** Description of ideal crown preparation and schematic design of five tooth preparations.

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and advanced color scanning features was used to scan all the CoCr crowns. To ensure that the scanning conditions (angle and position) were the same for each crown, all the crowns were fixed on the scanning disc with plasticine, with its intaglio surface maintained upward and perpendicular to the plane of the base. The clear and complete intaglio surfaces data of actual crowns from the SLM technique were obtained (n = 10 for each design group). Finally, the data of actual crowns were numbered from 1 to 10.

Next, the design crown, actual crown, and reference preparation (margins and interior) data were imported into Studio software, and the best-fit-algorithm was implemented on design crown and reference preparation, actual crown and reference preparation, respectively. With reference to previous research methods,[13] the detailed implementation procedure of the study is shown in Fig. 2. The fit discrepancies of design crowns, which are the result of registration between the intaglio surfaces of design crown and reference preparation, represent the effect of the CAD process on crown fit. The fit discrepancies of the actual crown are the result of registration between the intaglio surfaces of the actual crown and reference preparation, representing the effect of both the CAD and SLM processes on the fit of crowns. The fit-discrepancies in the SLM process itself were calculated by subtracting the deviations of the intaglio surfaces of the design crown (CAD process) from the deviations of the intaglio surfaces of the actual crown (CAD and SLM processes).

The fit discrepancies of crowns were evaluated based on the color-coded images. The colored segments represented the fit discrepancies of crowns, with positive discrepancies (larger crown) representing the outward distance away from the preparation surface and negative discrepancies (smaller crown) representing the inward distance away from the preparation surface. The fit discrepancies between the reference preparations and the intaglio surface of the design and actual crowns were also evaluated by the root-mean-square (RMS) as follows:

$$RMS = \frac{1}{\sqrt{n}} \sqrt{\sum_{i=1}^{n} \left(x_{1,i} - x_{2,i}\right)^2}$$

where $x_{1,i}$ is the measurement point i on the reference data, $x_{2,i}$ is the measurement point i on the test data, and n is the total number of measurement point pairs on each sample.[24]

Statistical analysis was performed in SPSS20.0 (IBM SPSS Inc., Chicago, IL, USA). The Shapiro Wilk normality test and homogeneity of variance test were adopted for analyzing the data of marginal and internal fit discrepancies obtained in CAD and SLM processes. The data that met the normal distribution and homogeneity of variance is expressed as means and stan-

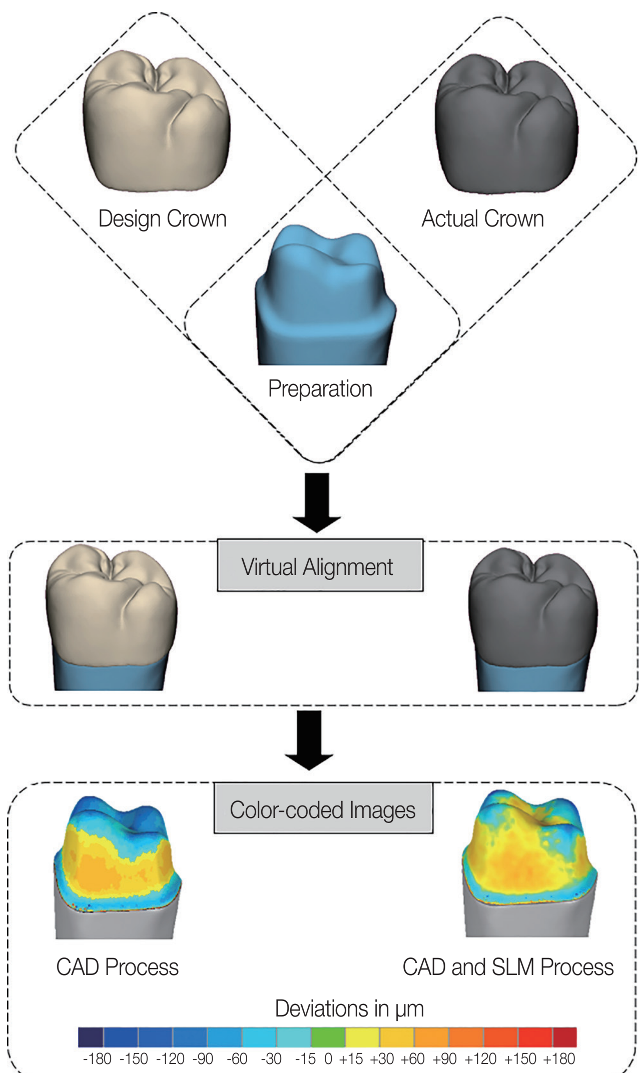


**Fig. 2.** The intaglio surfaces data of design and actual crowns in each design group were aligned to the virtual image of the reference preparation and color-coded difference images; 15 colored segments were calculated.

dard deviation. Next, a one-way analysis of variance (one-way ANOVA) was performed when the means were not all the same. Tukey's test was used for pairwise comparisons between groups. If there were abnormalities or heterogeneity of variance, data were expressed as median and interquartile range. Next, the Kruskal-Wallis H test was used for comparison and multiple comparisons. The significant level was set as α = .05.

## RESULTS

Fig. 3 depict the marginal or internal color-code differences of crowns in all five design groups were not identical in the CAD process. The chamfer and the feather group had similar marginal and internal color-code difference distributions, and the 135° group, shoulder-lip group, and the sharp line angles group had similar internal color-coded difference images. The axial area of each design group showed positive discrepancies (range: 15 to 60 µm), while the margins of the 135° group and the shoulder-lip group showed negative discrepancies (range: -15 to -30 µm).

According to Table 1, significant differences were detected among the five design groups in the margins or interiors of the crowns in the CAD process ($P$ < .001). The mean values of marginal and internal fit discrepancies were 10.0 to 24.2 µm and 29.6 to 31.4 µm, respectively. Among all the design groups, the marginal fit discrepancies of the shoulder-lip group margins (24.2 ± 3.2 µm) were the largest ($P$ < .01). Compared to the chamfer group (29.8(0.3) µm), the sharp line angles group (31.2(1.2) µm) had greater internal fit discrepancies ($P$ < .05).

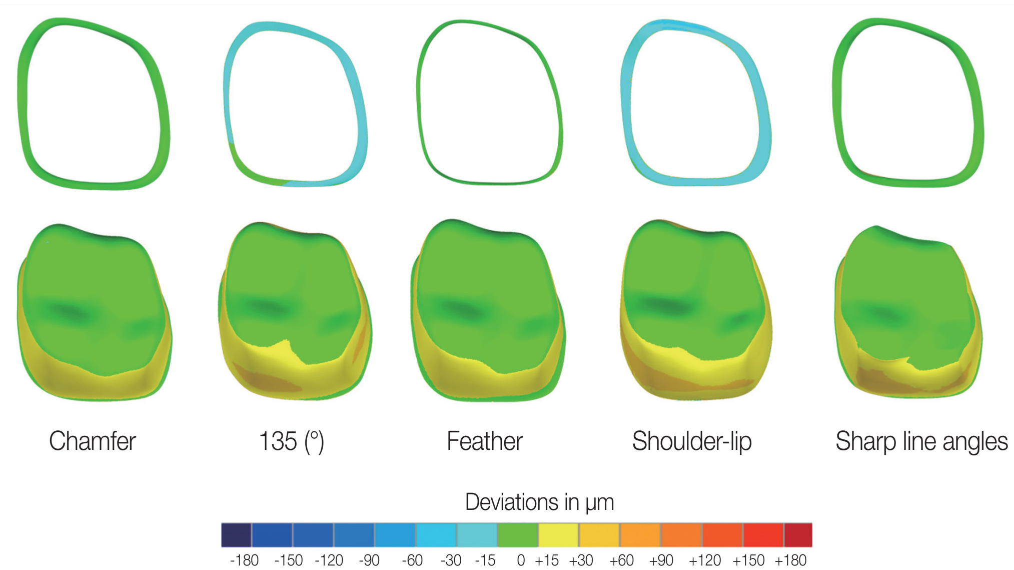


**Fig. 3.** Typical color-code difference images of crowns in each design group after the CAD process. The upper column represents the view of the marginal area from the occlusal surface, and the lower column represents the view of the internal area at 45°.

**Table 1.** The marginal and internal fit-discrepancies of crowns in each design group in terms of the CAD process (n = 10, µm)

| Area | Chamfer | 135° | Feather | Shoulder-lip | Sharp line angle | F/H | $P$ |
|---|---|---|---|---|---|---|---|
| Marginal | 14.0 ± 1.2$^{c}$ | 19.2 ± 2.4$^{b}$ | 10.0 ± 1.7$^{d}$ | 24.2 ± 3.2$^{a}$ | 11.5 ± 2.3$^{cd}$ | F = 68.237 | < .001 |
| Internal | 29.8(0.3)$^{b}$ | 31.0(0.6)$^{ab}$ | 29.6(2.0)$^{b}$ | 31.4(1.2)$^{a}$ | 31.2(1.2)$^{a}$ | H = 24.944 | < .001 |

The marginal data were displayed using the mean and standard deviation (one-way ANOVA and Turkey's test was used for comparisons), and the internal data were displayed by median and interquartile range (Kruskal-Wallis H test was used for comparisons). Different superscripts letters within each row indicate statistically significant differences ($P$ < .05).

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Fig. 4 depict the color-code difference images of marginal or internal of the actual crowns among all five design groups differed from each other after the superposition effect of the CAD and SLM process. There was a various color-coded interphase distribution in the marginal area, from yellow positive discrepancies (range: 15 to 60 µm) to negative blue discrepancies (range: -15 to -90 µm) in the shoulder-lip group compared to the other design groups. In the internal area, the non-smooth surfaces, such as cusps and sharp line angles in each design group showed sharp blue negative discrepancies (range: -15 to 90 µ m) distribution with different sizes, while the other regions showed green (range: -15 to 15 µm) or yellow discrepancies (range: 15 to 30 µm).

According to Table 2, the marginal or internal fit discrepancies in five design groups revealed significant differences after the superposition effect of the CAD and SLM processes (*P* < .001). In terms of marginal fit, the mean discrepancies ranged from 18.4 to 40.9 µm. The shoulder-lip group (40.9 ± 3.9 µm) had the greatest marginal fit discrepancy (*P* < .001), followed by 135° group. The chamfer group, feather group, and the sharp line angle group were the smallest, and there was no significant difference among the three groups (*P* > .05).

In terms of internal fit, the mean discrepancies ranged from 39.1 to 47.1 µm. The shoulder-lip group margins (47.1 ± 2.9 µm) and the sharp line angle group (44.5 ± 2.5 µm) showed larger fit discrepancies than the other three design groups (*P* < .05). Yet, there was no significant difference among the chamfer group, 135°group, and feather group (*P* > .05).

According to Table 3, the marginal or internal fit

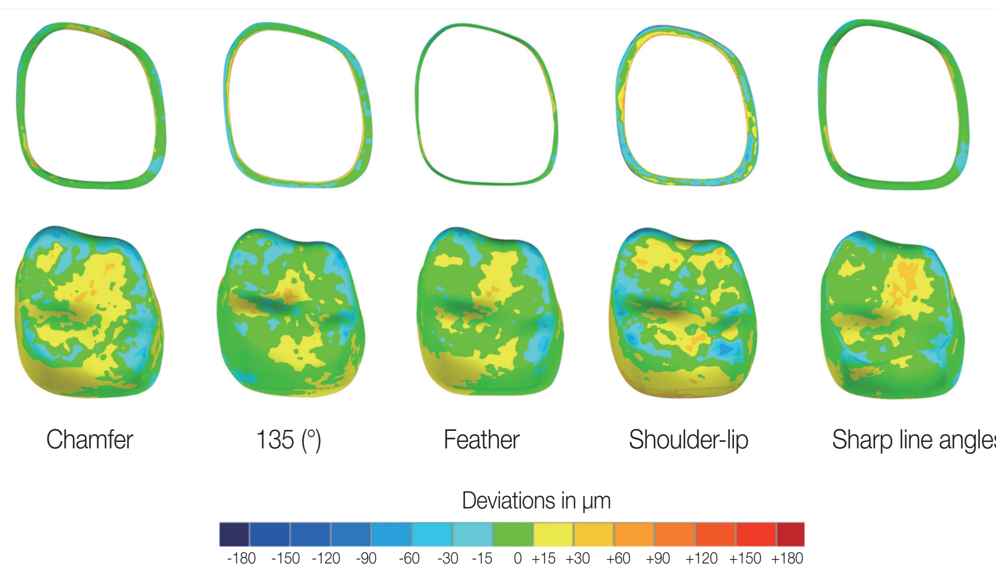


**Fig. 4.** Typical color-code difference images of the actual crowns in each design group after the CAD and SLM process. The upper column represents the view of the marginal area from the occlusal surface, and the lower column represents the view of the internal area at 45°.

**Table 2.** The marginal and internal fit-discrepancies of crowns in each design group after the CAD and SLM processes (n = 10, µm)

| Area | Chamfer | 135° | Feather | Shoulder-lip | Sharp line angle | F | *P* |
|---|---|---|---|---|---|---|---|
| Marginal | 20.0 ± 2.3$^{c}$ | 25.6 ± 2.3$^{b}$ | 20.8 ± 2.6$^{c}$ | 40.9 ± 3.9$^{a}$ | 18.4 ± 2.0$^{c}$ | 115.858 | < .001 |
| Internal | 40.0 ± 1.6$^{b}$ | 39.9 ± 3.3$^{b}$ | 39.1 ± 1.5$^{b}$ | 47.1 ± 2.9$^{a}$ | 44.5 ± 2.5$^{a}$ | 20.299 | < .001 |

The marginal and internal data were displayed using the mean and standard deviation(one-way ANOVA and Turkey's test was used for comparisons), and different superscripts letters within each row indicate statistically significant differences (*P* < .05).

**Table 3.** The marginal and internal fit-discrepancies of crowns in each design group in terms of the SLM process itself (n = 10, μm)

| Area | Chamfer | 135° | Feather | Shoulder-lip | Sharp line angle | F | *P* |
|---|---|---|---|---|---|---|---|
| Marginal | 6.0 ± 3.1[c] | 6.4 ± 3.8[c] | 10.8 ± 3.1[b] | 16.7 ± 3.3[a] | 6.9 ± 2.0[bc] | 21.306 | < .001 |
| Internal | 9.8 ± 1.4[b] | 9.0 ± 3.3[b] | 9.4 ± 1.6[b] | 15.7 ± 3.1[a] | 13.6 ± 2.7[a] | 13.735 | < .001 |

The marginal and internal data were displayed using the mean and standard deviation (one-way ANOVA and Turkey's test was used for comparisons), and different superscripts letters within each row indicate statistically significant differences ($P < .05$).

discrepancies in the five design groups in terms of the SLM process itself were significantly different ($P < .001$). Regarding marginal fit, the mean discrepancies of the five design groups ranged from 6.0 to16.7 μm. The shoulder-lip group margin group (16.7 ± 3.3 μm) had a greater marginal fit discrepancy ($P < .05$), followed by the feather group. However, there was no significant difference among the chamfer group, 135° group, and the sharp line angles group ($P > .05$).

Regarding internal fit, the mean discrepancies in all design groups ranged from 9.0 to 15.7 μm. The shoulder-lip group (15.7 ± 3.1 μm) or the sharp line angle group (13.6 ± 2.7 μm) had greater fit discrepancies ($P < .05$) compared to the other three groups, while the chamfer group, 135° group, and the feather group showed no significant difference ($P > .05$).

## DISCUSSION

Impression,[25,26] scanning electron micrographs (SEM),[27] and microcomputed tomography (micro-CT)[28] are often used to evaluate the marginal and internal fit of restorations. Nevertheless, these methods are limited by specimen damage,[28] measurement points,[29] and indirect data collection.[30] The present study evaluated the fit discrepancies of CoCr crowns with the color-coded difference in the images and the RMS values of the distance between the spatial points after the best-fit algorithm in Studio. The color-code difference in the images showed the positive or negative discrepancies of each part of a crown that compensated for the limitation created by RMS values, thereby making the experimental results comprehensive and reliable. Among the SLM techniques, the five different preparation designs showed different effects on the marginal or internal fit discrepancies of CoCr crowns in the CAD and SLM processes. Therefore, the hypothesis of this study was rejected.

The CAD process is the first key component in the workflow before restoration fabrication; however, its effect on the fit of restorations is seldom discussed. Our data showed that after the CAD process, the shoulder-lip group had the largest marginal fit discrepancies among all other groups, and the sharp line angle design significantly affected the internal fit of the crowns (Table 1). In the CAD process of crowns, it is necessary to extract the marginal feature lines and generate the required data of restorations radially and axially along with the data of tooth preparation surfaces according to the closed marginal feature lines. In such a process, the extraction of marginal feature lines is the key step, which includes pre-processing the triangular grid data, estimating grid points' curvature, searching for key feature points, and dividing the feature regions.[31,32] The design software automatically calculates or smoothens the offsets in the face of surface features with large curvature changes, such as thin margins or sharp line angles. The restorations with software-based or smoothened offsets may have great discrepancies with preparation surfaces.[33] Such discrepancies affect the quality of the restorations produced and have an adverse impact on the subsequent fabrication workflow.

The fabrication process is the second key workflow after the CAD process. In this study, the shoulder-lip group had greater marginal or internal fit discrepancies, while the sharp line angles group had greater internal fit discrepancies (Table 2). These results suggest that tooth preparation's marginal design has some influence on internal fit discrepancies of crowns, which is related to the calculation of restoration generated by CAD software mentioned above

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and the inherent constraints of the SLM process's self-forming principle. When restoration is formed with the SLM technique, the molten pool formed by laser sintering may sink into the powder due to the gravity and capillary action, resulting in deformation of the hanging structure and eventually affecting its formation accuracy.[34] Therefore, not all the restoration structures can be truly and perfectly formed in the SLM process. Typically, adding a support structure on the surface of the workpiece is sufficient to prevent subsidence. Still, for geometric shapes with greater curvatures, such as thin walls and sharp angles, the surface contour information between the slices is not taken into account, resulting in "step effect" that is created when the external surface of the material object is composed of the contour enveloping surfaces of several slicing layers.[35,36] Such an error, which is mainly affected by the forming direction, surface curvature, and slice thickness, can be reduced by making thinner slices, albeit it cannot be eliminated. Moreover, in the actual forming process, the effect of laser spot diameters on the actual dimensions formed of thin walls, sharp angles, and other fine structures shall also be considered.[36] Similarly, tooth preparation designs with thin walls and sharp angles are preferably avoided in clinical practice.[20,37]

The effects of the CAD and the fabrication process on the crowns' fit discrepancies may result in the superposition effect of homologous discrepancies or the offset effect of positive and negative discrepancies. In this study, compared with the marginal or internal fit discrepancies after the CAD process, all design groups after the SLM process had larger (positive values) marginal or internal fit discrepancies (Table 3). These data demonstrated that the products of digital dental workflows reflected the superposition effect of positive discrepancies of the CAD and SLM processes. Combined with the color-coded images and RMS analysis results in this study, the groove or sharp line angle preparation design further reduced the fit of final restorations, which might have an adverse effect on the longevity of both the restoration and the abutment tooth.

According to the existing scientific evidence, the maximum marginal or internal gap that was clinically acceptable for fixed restorations has not yet reached a broad consensus. Most research reports have found that the marginal and internal fit values vary between 50 - 100 µm[38,39] and 100 - 200 µm,[40] respectively. The study found that the effect of the CAD or fabrication process on the fit of all design groups was smaller than 25 µm. The fit discrepancies of the actual crowns after the CAD and SLM fabrication process were also smaller than 50 µm in this study, which is lower compared to most of the previously reported values.[38,40] The current results are related to the preset cement gap (30 µm) and extra cement gap (50 µm) in the CAD process and the evaluation method selected for the study. The color-coded images and RMSs after the best-fit-algorithm of the digital point cloud (> 100,000 data points) in this study were used to represent the virtual fit discrepancies. Such a digital point cloud arrangement had an inherent mathematical tendency to minimize the distance between tooth preparation and crown. However, in the study of an actual cement layer, any marginal or internal physical obstacles in a crown will magnify the mismatch between the crown and preparation into the thickness of the cement layer, which is why it is of essential importance to grind out such obstacles before the clinical cementation of the restoration.[12]

The present study has some limitations. First of all, the study introduced processing factors such as optical scanning in order to obtain data on the intaglio surface of the crown. Although the selected model scanner has a scanning accuracy of 4 µm, this may still affect the fit discrepancies of the SLM step itself to a certain extent. In addition, the study did not really measure the gap between the crown and the tooth preparation, and the best-fit-algorithm of Studio failed to stimulate the actual "running track" of the application of a crown to preparation in clinical practice; hence, the fit discrepancies may be different from the actual one in clinical practice. Finally, only a set of cement gap values was set in the experiment to study the fit discrepancies of CoCr alloy materials with the SLM technique. In clinical practice, more factors, including the flow of the resin cement, may affect the final fit of the crown. In the future, the fit discrepancies of each step of SLM technique should be further studied by changing the present value of the cement gap.

## CONCLUSION

Both the CAD and SLM processes affected the marginal or internal fit of CoCr crowns, which varied based on the preparation designs. Typically, the shoulder-lip and sharp line angles designs had a more significant effect on crowns marginal or internal fit. However, the differences between the design groups were relatively small, especially when compared to fit discrepancies observed clinically.

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