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Original Article

Influence of finish line quality and axial surface location on marginal adaptation of selective laser melting fabricated copings

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Selective laser melting (SLM)

Abstract *Background/purpose:* The digital transition in dentistry necessitates reexamining traditional preparation standards, particularly finish-line quality for 3D-printed restorations. This study investigated how finish-line characteristics affect the marginal adaptation of selective laser melting (SLM) fabricated copings.
Materials and methods: Forty typodont maxillary central incisors prepared for porcelain-fused-to-metal crowns were scanned. Margin width, margin curvature, and finish-line curvature were measured at four axial surfaces. Finish lines were graded on a 1—4 scale based on distinctness and continuity. The maximum marginal gap at each surface of every SLM-printed coping on its respective abutment was recorded and categorized as excellent (120 μm). Friedman and Wilcoxon signed-rank tests assessed marginal gaps; repeatedmeasures ANOVA and McNemar—Bowker tests evaluated categorical outcomes. Generalized estimating equations (GEE) estimated odds ratios for poor adaptation ($\alpha=0.05$).
Results: Marginal gaps on mesial (79.75±42.39 μm) and distal (86.48±32.49 μm) surfaces were significantly larger than labial (25.35±39.76 μm) and palatal (39.83±52.17 μm) surfaces (P0.05).
Conclusion: Finish-line distinctness and axial surface location were the important determinants of SLM coping adaptation. Even in digital workflows, meticulous tooth preparation

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remains essential, while evaluation rubrics may recalibrate the weighting of finish-line continuity and smoothness.

Introduction

Digital dentistry has transformed restorative dentistry by introducing high precision and efficiency through computer-aided design and manufacturing (CAD/CAM) technologies. Among these, 3D metal printing, particularly selective laser melting (SLM), has become a promising method for fabricating dental copings and frameworks.[1—3] While 3D-printed restorations offer superior material efficiency and design flexibility over conventional methods, their clinical success still hinges on optimal marginal fit.[4,5]

The marginal gap, defined as the vertical discrepancy between the restoration margin and the tooth preparation, significantly affects clinical outcomes. Gaps exceeding 120 μm may lead to cement dissolution, microleakage, and subsequent biological complications.[6] Gold-casting restorations have long achieved marginal gaps below 40 μm, establishing this threshold as the ideal clinical target for cemented restorations.[7,8] Digital dentistry should not only meet this threshold, but rather leverage its technological advantages to achieve consistently superior marginal adaptation.[4,5,9]

In conventional workflow, ideal marginal fit depends in a large part on tooth preparation quality, impression accuracy, wax pattern design, and fabrication precision. Among these, finish line quality, the critical transition between the prepared and the unprepared tooth structure, is foundational for proper marginal adaptation. The location and curvature of finish line have been shown to significantly affect the marginal gap of copings. Specifically, subgingival finish lines encounter a greater marginal misfit compared to supragingival ones;[10,11] a greater finish line curvature has been associated with increased marginal gaps in casting-fabricated copings.[12—14]

The transition from conventional to digital workflows demands reevaluation of traditional preparation criteria.[15,16] Although SLM can faithfully reproduce scanned preparations, its stair-step effect of layer-by-layer addition and residual stress generated during printing can compromise dimensional accuracy and surface finish.[17] Further, these effects are amplified on curved surfaces,[18—20] raising the concern that preparation finish lines commonly follow the tooth contour and the curvature of free gingival margin. Moreover, the influence of nonideal finish lines, especially those with indistinct margins or complex geometries commonly found in the clinic,[21,22] on the marginal fit of SLM-fabricated copings remains poorly understood and warrants further investigation.[23—29]

Previous studies have extensively assessed marginal accuracy across digital and conventional fabrication methods.[5,30] But most use idealized preparations that do not capture clinical variability.[27] However, it was revealed that more than 90 % of preparations exhibited suboptimal finish line characteristics,[21] and dental students often demonstrated deficiencies in finish line execution.[31,32] This gap between controlled research and clinical reality raises critical questions regarding the applicability of existing marginal gap data to real world scenarios.

This study was to evaluate how tooth finish line quality affects the marginal gap of SLM-fabricated copings using typodont preparations by dental students. By situating the investigation in a realistic educational setting, our objective was to bridge the gap between idealized experiments and clinical practice, offering actionable insights for dental training and digital workflow refinement. The null hypothesis was that abutment finish line quality and geometry would not influence the marginal gap of SLM-fabricated copings.

Materials and methods

Forty typodont maxillary right central incisors (PRO2002; Nissin Dental Products, Kyoto, Japan), one per student of the fifth-year class of National Yang Ming Chiao Tung University, were prepared during a clinical competency examination for porcelain-fused-to-metal (PFM) crown fabrication. Typodont models were chosen to simulate clinical conditions while ensuring standardization. After faculty approval, each specimen was scanned with a Medit T710 desktop scanner (Medit, Seoul, Republic of Korea; claimed 7 μm accuracy). To ensure precise finish line data, each abutment was scanned following the manufacturer's protocol under controlled ambient lighting.

The students were instructed to design copings in Exocad DentalCAD v3.2 (Exocad GmbH, Darmstadt, Germany) with the following parameters: a minimum coping thickness of 0.5 mm; a cement space of 50 μm; and a 1 mm "margin zone" (the distance from the cement space to the finish line). The finish line was initially traced automatically using the software's built-in algorithm. The finish line was then meticulously reviewed and adjusted by a single calibrated experienced instructor (Chen) to ensure standardization and adherence to the defined preparation margin. A digital cutback for PFM was applied to ensure adequate porcelain space.

The copings were fabricated on a selective laser melting system (D-150; Guangzhou Riton Additive Technology, Guangzhou, China) using Co—Cr—W powder (Guangzhou Riton Additive Technology), in accordance with the manufacturer's instructions. Printing parameters were set to a layer thickness of 25 μm, laser power of 200 W, and a scan speed of 800 mm/s. After printing, support structures were removed and copings were sandblasted with 100 μm aluminum oxide at 2 bars to remove the oxidation layer. Students then performed a coping try-in to ensure complete seating by adjusting only the internal surface using a small carbide round bur and Fit Checker Advanced (GC America, Alsip, IL, USA) as a disclosing medium. The complete seating of the coping was confirmed when the Fit Checker film exhibited a uniform minimal thickness without internal breakthrough areas, except at the margin where the perforation indicates proper expression of the material. Critically, any alteration of the coping margin was strictly prohibited to isolate the influence of preparation defects on the marginal fit.

A spring-loaded holding device was used to apply a uniform load to each coping seated on its respective abutment. The assembly was inspected using a 360-degree external observation protocol with a 2.5D automatic vision measuring machine (AF3020, Nan Jie, Taichung, Taiwan), and the maximum gap between the coping margin and the finish line on each axial surface was recorded. The marginal gaps recorded were subsequently classified as excellent if (<40 μm), acceptable (40–120 μm), or poor (>120 μm).[33]

Finish line quality on each surface of the digital abutments was assessed independently and in a blinded fashion by two experienced instructors (Wang and Liu). A four-grade system (Fig. 1) was used to classify the results. Interrater reliability of this system was calculated using the intraclass correlation coefficient (ICC), yielding 0.892, which indicates excellent agreement. Although a fully objective metric for finish line quality remains difficult to establish, the adopted four-grade system was based on well-defined, clinically relevant characteristics (distinctness, continuity, and presence of defects). The high ICC supports the consistency and utility of this classification for evaluating the complex geometry of student-prepared finish lines. In addition, finish-line curvature on each surface was measured in 3D Slicer software (Kitware, Clifton Park, NY, USA). Margin width and margin curvature were recorded at the central axis of each axial surface (mesial, distal, labial, and palatal) of the abutments (Fig. 2).

Statistical analyses were performed in SPSS Statistics v29 (IBM, Armonk, NY, USA). Data normality and variance homogeneity were evaluated with Shapiro–Wilk and Levene tests, respectively. Marginal gaps across the four surfaces were compared using the Friedman test for related samples. Marginal quality categories were assessed using repeated measures ANOVA and McNemar–Bowker tests. The effects of finish line location and quality on graded marginal gap were assessed using generalized estimating equation (GEE) analyses with an ordinal logistic model. Statistical significance was set at $\alpha = 0.05$.

Results

The Friedman test revealed significant differences in marginal gaps across the four axial surfaces. Wilcoxon signed-rank test with Bonferroni correction showed that marginal gaps at mesial and distal surfaces were significantly larger than those on labial and palatal surfaces (Table 1). When gaps were classified as excellent, acceptable, and poor, the McNemar–Bowker test indicated a superior margin quality on the labial and palatal surfaces ($P < 0.05$).

Table 2 summarizes the descriptive statistics for the finish line quality. The ICC for finish line assessments for two raters was 0.892 indicating excellent agreement. Repeated-measures ANOVA with Bonferroni-adjusted pairwise comparisons ($P < 0.05$) showed that the labial surface exhibited the greatest margin width and the lowest curvature for both margin and finish line. Curvature was expressed as 1/length, so smaller values indicate more obtuse angles. Compared to the labial surface, the mesial and distal surfaces displayed narrower margin widths and higher curvature at both the margin and finish line. Finish line quality also differed significantly across surfaces (McNemar–Bowker test, $P < 0.05$) revealed superior quality on the labial surface compared to the palatal and distal surfaces. Specifically, 52.5 % of labial finish lines were Grade 1, whereas 37.5 % of palatal finish lines were Grade 4.

GEE analyses revealed that, relative to the labial surface, mesial and distal surfaces had significantly higher odds of poor coping adaptation (Table 3). Partially indistinct or defective finish lines were associated with the likelihood of larger marginal gaps versus distinct Grade 1 lines. In contrast, margin width, margin curvature, and finish line curvature did not significantly predict marginal gap

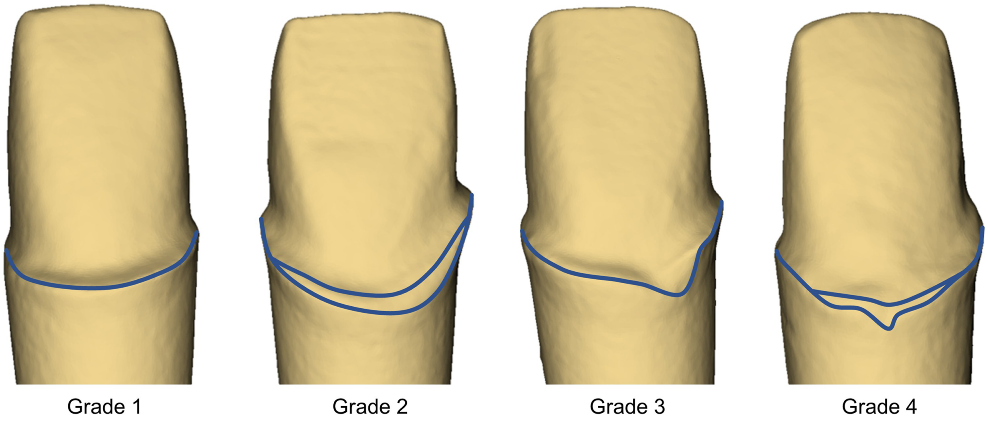

Figure 1 Finish line classification: continuous and distinct (Grade 1), continuous with partially indistinct zones (Grade 2), distinct but with defects (Grade 3), indistinct with defects (Grade 4).

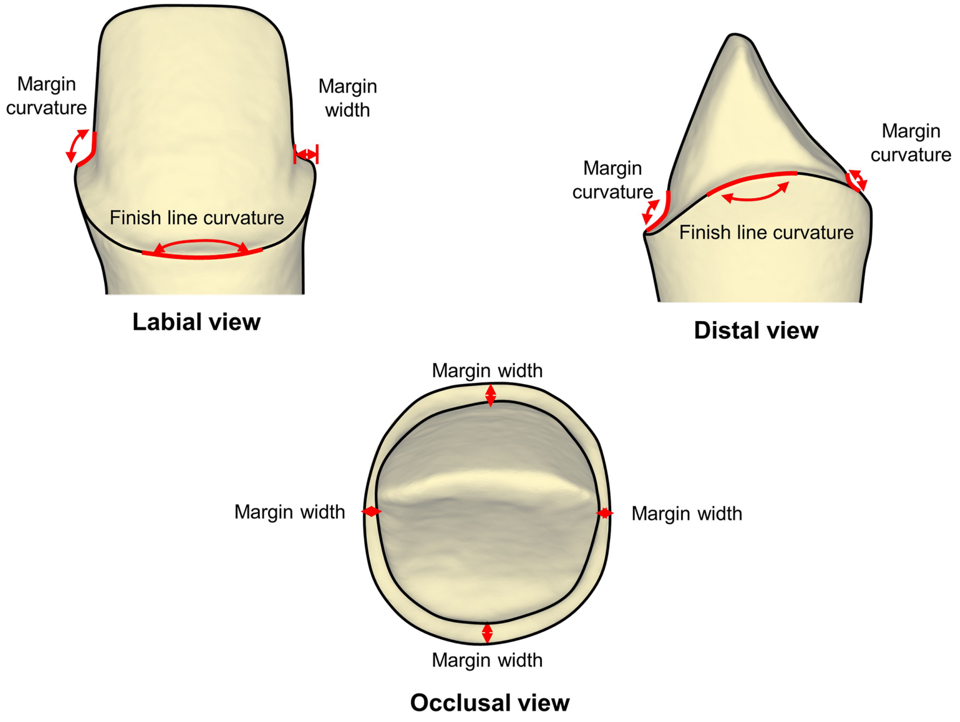

Figure 2 Measurements of finish-line curvature, and margin width and margin curvature at the central axis of each axial surface.

Table 1 Distribution and comparison of the marginal gap of the coping were assessed at four axial surfaces. The maximum marginal gap at each surface was categorized as follows: Excellent (<40 μm), Acceptable (40—120 μm), and Poor (>120 μm).

Marginal gap ($N = 40$)	Mean (SD)	Range	Coping margin quality (%)			McNemar—Bowker Test[a]
			Excellent	Acceptable	Poor	
Labial	25.35 (39.76)	0—161	27 (67.5 %)	12 (30 %)	1 (2.5 %)	A
Mesial	79.75 (42.39)	15—237	4 (10 %)	32 (80 %)	4 (10 %)	B
Palatal	39.83 (52.17)	0—158	25 (62.5 %)	13 (32.5 %)	2 (5 %)	A
Distal	86.48 (32.49)	28—172	3 (7.5 %)	32 (80 %)	5 (12.5 %)	B

[a] Different capitals denote significantly different among 4 sites ($P < 0.05$).

($P > 0.05$). Margin width approached but did not reach significance ($P = 0.074$).

Discussion

Marginal fit of crowns and bridges is critical for long-term clinical success, regardless of fabrication technique, whether by lost-wax casting, CAD/CAM, or digital printing.[4,27] Yet, most studies rely on idealized abutments with continuous finish lines, overlooking clinical variability.[4,22,27] To our knowledge, this is the first study to evaluate how finish line distinctness and smoothness affect marginal adaptation of SLM-fabricated copings under realistic, student-prepared conditions. Our results show that continuous and distinct finish lines (Grade 1) produced significantly smaller marginal gaps, whereas indistinct or defective lines (Grades 2—4) greatly increased the chances of poor adaptation (Table 3). In contrast, margin width, margin curvature, and finish line curvature did not significantly predict marginal misfit, leading to a partial rejection of the null hypothesis. These results underscore that achieving optimal marginal fit remains paramount to restoration longevity.

Although digital workflows automate and standardize steps, they remain highly sensitive to input data quality, particularly the geometry and clarity of tooth preparation margins.[3,9,11] Indistinct or discontinuous finish lines compromise scanning accuracy, as scanners rely on clear geometric landmarks.[24] Poorly defined finish lines can produce uneven light reflection and require repeated scans, increasing both time and error risk. Software algorithms may then misidentify or over-smooth the finish line, resulting in a compromised digital model.[23] During CAD, ambiguous finish lines can lead to incorrect margin tracing,[28] further exacerbating design discrepancies. Moreover, the layer-by-layer construction process in SLM can amplify these errors, particularly in regions of complex geometry or steep curvature.[4,17,25,26] Our results confirm these challenges and extend them to the realm of 3D metal printing.

Table 2 Descriptive statistics of measuring factors including margin width, margin curvature, finish line curvature, and finish line quality across four axial surfaces.

Variable	Labial	Mesial	Palatal	Distal
Margin width (mm)	0.99 (0.23)^{a}	0.64 (0.14)^{c}	0.82 (0.17)^{b}	0.66 (0.15)^{c}
Margin curvature (1/mm)	0.78 (0.21)^{c}	0.88 (0.25)^{ab}	0.84 (0.24)^{bc}	0.98 (0.25)^{ab}
Finish line curvature (1/mm)	0.31 (0.05)^{b}	0.38 (0.12)^{a}	0.38 (0.05)^{a}	0.39 (0.11)^{a}
Finish line grade[a]	Labial^{a}	Mesial ^{ab}	Palatal^{b}	Distal^{b}
Grade 1	21 (52.5 %)	12 (30.0 %)	11 (27.5 %)	8 (20.0 %)
Grade 2	13 (32.5 %)	12 (30.0 %)	11 (27.5 %)	14 (35.0 %)
Grade 3	1 (2.5 %)	8 (20.0 %)	3 (7.5 %)	10 (25.0 %)
Grade 4	5 (12.5 %)	8 (20.0 %)	15 (37.5 %)	8 (20.0 %)

Different superscript letters indicate statistically significant differences in measuring factors across 4 sites ($P < 0.05$).

[a] Finish line grading: 1. Continuous and distinct, 2. Continuous with partial indistinct, 3. Distinct with defect, 4. Indistinct with defect.

Table 3 Generalized Estimating Equation (GEE) results for factors influencing the marginal gap of SLM-fabricated copings.

Variable	β Coefficient (SE)	Wald χ^2	*P*-value	Adjusted odds ratio (95 % CI)
Site				
Labial (Referent)				
Mesial	3.351 (0.8384)	15.972	0.000[b]	28.52 (5.51–147.49)
Palatal	0.255 (0.5612)	0.206	0.650	1.29 (0.43–3.88)
Distal	3.482 (0.8893)	15.332	0.000[b]	32.54 (5.69–185.93)
Finish line grade[a]				
Grade 1 (Referent)				
Grade 2	1.294 (0.4636)	7.791	0.005[b]	3.65 (1.47–9.05)
Grade 3	1.589 (0.4942)	10.332	0.001[b]	4.90 (1.86–12.90)
Grade 4	1.698 (0.5474)	9.622	0.002[b]	5.46 (1.87–15.98)
Margin width	1.979 (1.1063)	3.200	0.074	7.24 (0.83–63.28)
Margin curvature	0.848 (0.7829)	1.173	0.279	2.34 (0.50–10.83)
Finish line curvature	−0.265 (2.1045)	0.016	0.900	0.77 (0.01–47.45)

[a] Finish line grading: 1. Continuous and distinct, 2. Continuous with partial indistinct, 3. Distinct with defect, 4. Indistinct with defect.

[b] $P < 0.01$.

An equally notable finding was the site-specific variation in the marginal gaps. Mesial and distal surfaces exhibited significantly larger gaps than labial and palatal surfaces (Table 1), despite their finish line quality, margin curvature, and finish line curvature were comparable to those of palatal surface (Table 2). This suggests that, beyond margin width, anatomical geometry specifically surface curvature and orientation substantially impact SLM fabrication outcomes. Previous studies reported that thin-wall warping and overhanging failures occur when parts lack adjoining bases in SLM printing.[19,20,25] Additionally, the direction of surface curvature (convex vs. concave) affects thermal stress dissipation, powder redistribution, and recoating uniformity during printing.[19,20] We hypothesize those concave surfaces from the perspective of the build direction, characteristic of the mesial and distal aspects of anterior teeth, are more prone to distortion and surface irregularities due to reduced support and more complex thermal gradients (Fig. 3). Conversely, convex surfaces on labial and palatal aspects benefit from better layer support and thermal stability, which may explain their superior marginal fit (Fig. 3). Therefore, adding auxiliary support structures on mesial and distal surfaces or optimizing build orientation to minimize overhang is recommended.

Interestingly, finish line curvature was not a significant predictor of marginal gap in our GEE model (Table 3). This contrasts with lost-wax studies showing that steep finish-line curvature compromises marginal accuracy of metal and ceramic copings.[12–14] In SLM, print quality is governed by layer thickness and slope angle inherent to the stair-step effect of the process.[17,25,26] This disparity may be because the absolute curvatures of finish lines at four axial surfaces were recorded for analyses, which did not consider upward or downward curvatures in this study.

According to previous research, deep chamfer design, compared to standard chamfer, achieved the lowest marginal gap in SLM-fabricated copings, particularly when paired with cobalt-chromium alloy.[4] In our study, neither margin width nor curvature alone predicted coping fit, even though labial surfaces with deep chamfer finish lines showed the best adaptation (Table 1). This discrepancy may stem from our measurement approach, which sampled only the midpoint width and curvature of the chamfer margin on each axial surface. Future work should use standardized abutments with systematically varied chamfer widths and

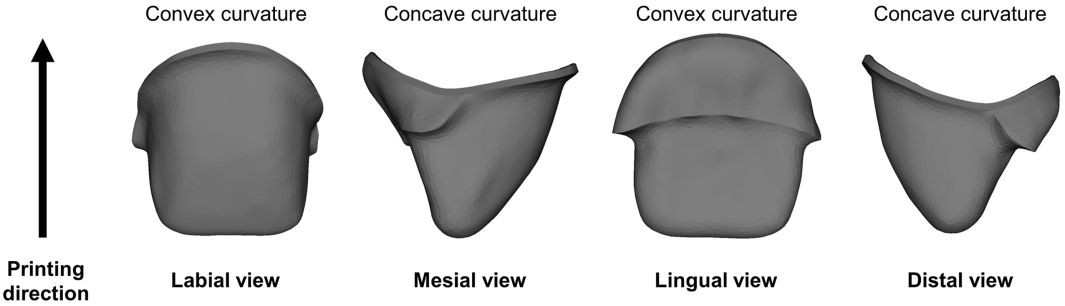

Figure 3 Schematic drawing of metal printing showing concave curvature of mesial and distal coping margins; and convex curvature of labial and palatal coping margins along with printing direction.

curvature profiles to isolate their true effects on marginal adaptation.

Using student-prepared typodont teeth is a major strength, yielding a realistic dataset versus idealized models. Our results confirm that most clinical preparations have suboptimal finish lines, and digital workflows cannot fully compensate for these deficiencies. Marginal fit is cumulative, influenced by scanning accuracy, CAD margin tracing, and post-printing adjustment. The student-led workflow, which included instructor-approved margins and minimal internal adjustment, was chosen to test the robustness of the SLM process under clinically relevant variability. CAD/CAM systems remain geometry-sensitive, often amplifying minor defects. Recent deep-learning approaches have improved margin recognition, yet automated tools for margin verification and coping design assessment remain underdeveloped and warrant further investigation.[34—37]

The decision to focus on the maximum gap per surface was a deliberate methodological choice. Although the average gap provides information on overall precision, the maximum gap represents the worst-case scenario and is widely regarded the most clinically critical parameter. A large maximum gap is the primary indicator of potential microleakage and is directly related to clinical failure (for example, secondary caries) of restoration. In this study, nine students (22.5 %) had at least one marginal gap $>$120 μm on their coping (Table 1); one student had two such failures and another had three. Only one student (2.5 %) achieved Grade 1 finish lines on all 4 axial surfaces, whereas 21 students (52.5 %) had at least one Grade 4 finish line (Table 2). Labial surfaces received superior grades more often, while palatal surfaces were disproportionately Grade 4 likely due to the small cingulum of the typodont resin tooth and limited direct visibility and access. From an educational standpoint, these findings highlight the need to refine and update the dental training curricula. As digital manufacturing becomes standard, objective and quantifiable metrics, such as finish line continuity and curvature, are increasingly essential to evaluate student performance.[31] Digital platforms including intraoral scanners, automated grading software, and haptic simulators can provide immediate feedback and help students refine their skills with a higher level of precision.[15] Moreover, digital self-assessment enhances student performance and reduces confusion often caused by inconsistent instructor evaluations.[16,32]

Clinically, this study underscores that digital workflows do not replace the need for meticulous tooth preparation.[22] In fact, the precision demands of CAD/CAM systems narrow error tolerances. Practitioners should be particularly cautious with anterior restorations, where the mesial and distal surfaces are at increased risk of marginal discrepancies due to geometric constraints. Pre-restorative assessment of margin clarity using high-resolution scans and the implementation of virtual design checkpoints can help mitigate these risks.

Despite offering valuable insights, this study has several limitations. The typodont model cannot fully reproduce natural tooth biomechanics or optical properties. Although the sample size detected significant effects, larger clinical studies are needed to assess long-term outcomes for restorations with compromised margins.[21,22] Future work should investigate AI-based margin detection, real-time digital feedback, and the combined effects of scanner type, build orientation, material properties, and post-processing on the digital workflow.

Based on the findings of this study, continuous, distinct finish lines (Grade 1) yielded significantly better marginal adaptation of SLM-fabricated copings, whereas margin width, margin curvature, and overall finish line curvature exerted minimal influence on marginal fit. In addition, the pronounced concave curvature of the mesial and distal surfaces during printing could be associated with greater margin misfit, identifying these regions as high-risk zones. Clinicians and educators should therefore pay particular attention to these surfaces during preparation and evaluation when working with SLM-fabricated copings.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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