Comparison of 3D-Printed Single Crown Outcomes Among Different Computer-Aided Design Software Programs

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Purpose: Low-cost resin 3D printers have been used to produce affordable interim single crowns in public and private dental practices. The purpose of this study was to assess the impact of different computer-aided design (CAD) software programs on 3D trueness, microscopic marginal and internal gaps, time to design, and interproximal contacts of low-cost 3D-printed single crowns. ***Materials and Methods:*** This in vitro study was performed on a total of 90 standardized resin-prepared teeth adapted to a dental manikin. For comparison among CAD software programs, 45 tooth preparations received 3D-printed crowns designed with one of three CAD software programs by an experienced technician and identified as groups TRIOS (n = 15), EXOCAD (n = 15), and ZZ (Zirkonzahn; n = 15). To assess interoperator reproducibility, 15 additional crowns were designed by a dental clinician (group ZZ-DENT) and 15 by a dental prosthetic technician (group ZZ-PROS), both with basic 1-week CAD/CAM training. Finally, as a control group, 15 crowns were milled using a high-end five-axis milling device (group ZZ-CONTROL). Statistically significant differences for 3D trueness, microscopic gaps, time to design, and interproximal contacts among groups were assessed with the Kruskal-Wallis test. ***Results:*** No statistically significant differences in 3D trueness or marginal or internal gaps were found, either among different software programs or CAD operators ($P > .05$). However, Group TRIOS took significantly longer to design than EXOCAD and ZZ groups ($P = .001$). Less-experienced operators were significantly outperformed in time and interproximal contacts ($P = .001$) by the CAD technician using the same software program. Finally, control milled crowns (ZZ-CONTROL) significantly outperformed the respective 3D-printed copies (ZZ) in all assessed variables ($P < .001$). ***Conclusions:*** Different CAD software programs may affect the time required to design, but they do not significantly affect clinical outcomes of low-cost 3D-printed resin crowns if designed by an experienced CAD technician. *Int J Prosthodont 2024;37(suppl):s63–s70. doi: 10.11607/ijp.8718*

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One of the main dental applications of CAD/CAM is digitally designing dental prostheses from intraoral scans using CAD software programs.[1] In this context, interim CAD/CAM prostheses can be manufactured with resin using 3D printers or milling devices, generally with better fit, accuracy,[2,3] and mechanical properties[4] than conventional resin prostheses.

Several factors involved in the three main steps of digital workflow in restorative dentistry (ie, image acquisition with optical scanners, CAD, and CAM) may affect the outcomes of final CAD/CAM dental prostheses.[1,3] In the CAD phase, the two main factors are the CAD software program and the operator's level of expertise to digitally design a prosthesis with satisfactory clinical characteristics.[5–7] Nevertheless, the aforementioned references were CAD studies that did not assess the impact of each factor on marginal fit and clinical outcomes of the manufactured interim crowns.

Among the most used methods by dental clinics and laboratories to fabricate interim CAD/CAM crowns are low-cost liquid crystal display (LCD) 3D-printers. These have a higher production rate and lower costs than milling devices to produce interim single crowns.[8] On the other hand, single crowns produced with LCD 3D printers are generally more operator-sensitive[1] and less accurate than milling devices.[8,9] Information about the impact of the CAD phase on the final result of single crowns manufactured with low-cost LCD 3D printers is lacking.

Thus, the aim of this study was to assess the impact of different CAD software programs on 3D trueness, marginal and internal gap, interproximal contacts (crown seating), and time required for digitally designed CAD/CAM single crowns.

MATERIALS AND METHODS

This in vitro study was conducted on 90 prefabricated, standardized, resin-prepared teeth mounted on a study dental manikin (AG-3, Frasaco) compatible with phantom head units. Each model had a total of four equigingival preparations: one molar, one premolar, one canine, and one incisor. All tooth preparations had sound adjacent teeth and an antagonist arch at the time of intraoral scanning (IOS). All dental models were scanned with the same intraoral scanner (Trios 4, 3Shape) as STL (standard tessellation language) files. These files were then checked in the software to confirm that the whole area had been scanned cleanly, without distortions due to irregular light reflection and with mesh integrity at the margin area.

Each STL file from IOS was first given to a CAD technician (ie, a dental prosthetic technician [J.F.L.] who also possess a certificate of CAD/CAM) with more than 5 years of experience in CAD to digitally design single crowns in all preparations using three different software programs: DentalCAD (Exocad; group EXOCAD), which is currently considered state-of-the-art and is one of the most used CAD software programs in dental laboratories; Dental System (3Shape), which is a CAD software integrated with the intraoral scanner used in this study (Trios 4; group TRIOS); and Modellier (Zirkonzahn; group ZZ), which is integrated with a high-end five-axis milling device of the same brand. The CAD technician experience was 6 years for Dental System and 8 years with both DentalCAD and Modellier. The three software programs were used in the same computer with high-end specifications and a dedicated graphic card, as recommended by the software manufacturers. To assess precision (ie, interoperator reproducibility), the latter software was also used by two other operators with different backgrounds who performed 1-week basic CAD training with the same system (ie, a dental clinician [group ZZ-DENT] and a dental prosthetic technician [group ZZ-PROS]). Figure 1 shows a flowchart of the study procedure. In addition, the time required to perform each digital design was recorded in minutes. All crown shapes had a predefined cement gap thickness of 35 μm and were obtained by mirroring the sound contralateral tooth and adjusted freely on the dental arch by the operators. The resulting digital crowns were saved as STL files (Fig 2).

All resulting STL files of single crowns were imported to a slicing software (Photon Workshop, Anycubic) and 3D-printed with a light-cured resin composed by oligomers and monomers (Cosmos A3, Straumann), using a low-cost LCD 3D-printer (Photon, Anycubic) with the following parameters: 50-μm layer thickness, 8 bottom layers with 80 seconds of exposure time, and 6 seconds of normal exposure time for the remaining layers. All 3D-printed crowns were also washed for 3 minutes with 99% isopropyl alcohol, dried and light-cured for 10 minutes in the UV light-curing chamber of the 3D-printer manufacturer (Wash & Cure 2.0, Anycubic), finished with a diamond bur kit (KG Sorensen) to remove the 3D-printed supports, and polished with a silicon acrylic polishing kit (JOTA). To prevent alterations of interproximal contact points, no supports were positioned on areas designed to have contact points. Therefore, no finishing or polishing procedures affected the interproximal contacts of the manufactured crowns.

In addition, all STL crowns in group ZZ were also milled with polymethyl methacrylate (PMMA; Temp, Zirkonzahn) using the milling machine (M1, Zirkonzahn) integrated with the CAD software used. All milling procedures were performed under the "quality" protocol, following the recommendation of the manufacturer. No postprocessing procedure was performed on the milled crowns other than removing the attachments that connected the crowns with the PMMA disc, followed by the same polishing procedure performed for the 3D-printed crowns.

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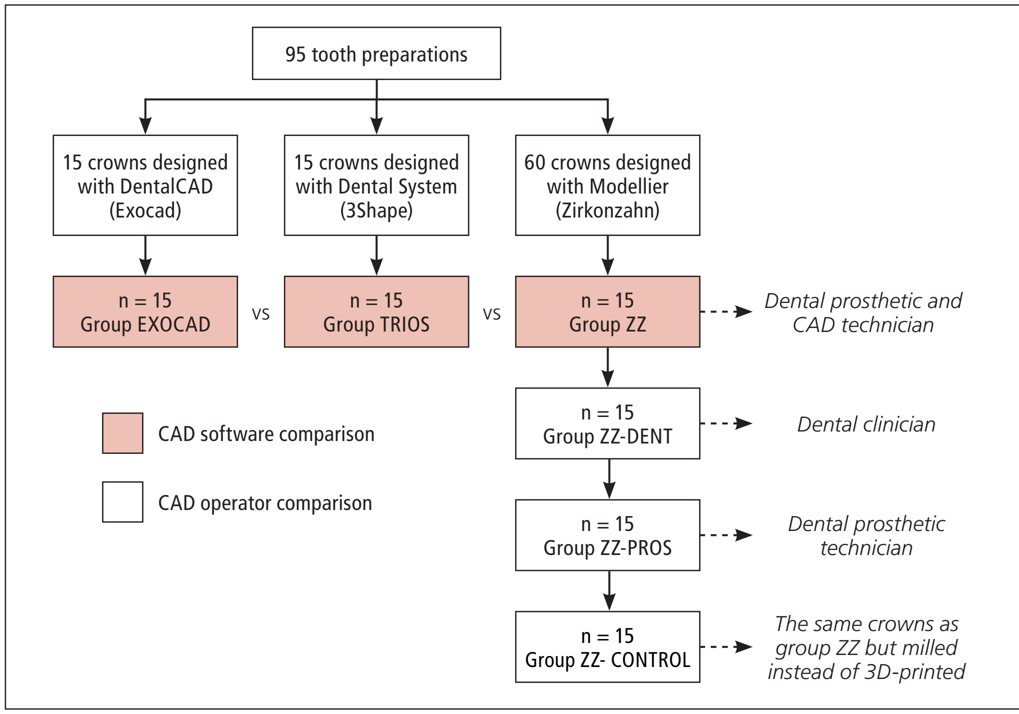
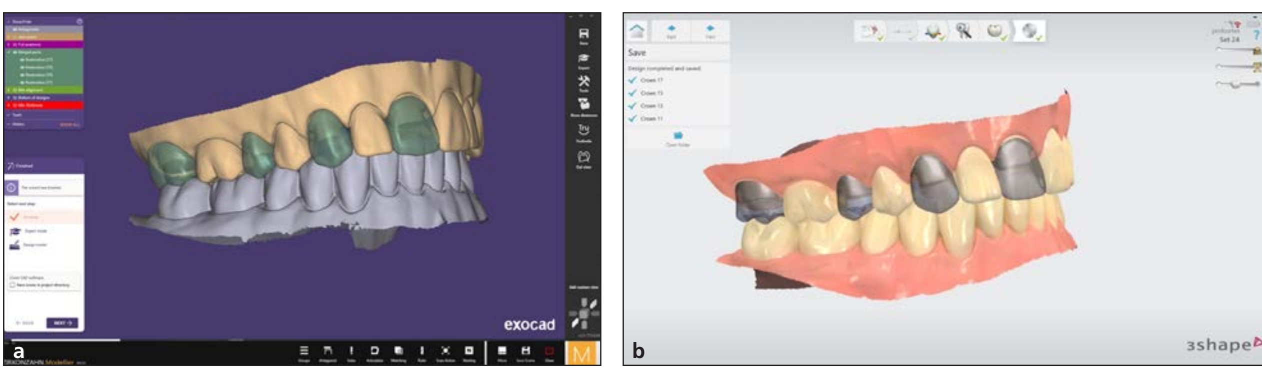


Fig 1 Flowchart of the study procedure.



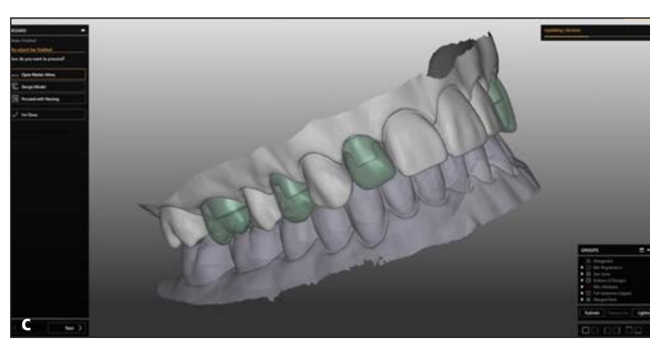


Fig 2 Digital designs were performed in the three CAD software programs: *(a)* DentalCAD, *(b)* Dental System, and *(c)* Modellier.

All manufactured crowns were tried in the dental manikin, and the interproximal contacts were tested with flossing and graded based on a previously described methodology[10] using the following three-point scale: *(1)* no chairside adjustments required (when both mesial and distal contacts with adjacent teeth were adequate and not interfering with crown seating); *(2)* chairside adjustments required (when either mesial or distal contacts were excessive, preventing adequate crown seating); or *(3)* crown remade required (when either mesial or distal contacts were absent).

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Table 1 Descriptive Quantitative Data and Statistical Differences Among CAD Software Groups of 3D-Printed Crowns

	Group TRIOS		Group EXOCAD		Group ZZ		
Variable	Median	Range	Median	Range	Median	Range	P^a
Marginal gap, μm	123.77	46.15–189.22	85.56	44.22–230.67	113.91	54.66–152.14	.457
Internal gap, μm	177.82	101.22–226.04	148.33	70.23–272.78	161.29	101.18–198.22	.374
Proximal deviation, mm	0.14	0.07–0.19	0.14	0.05–0.33	0.17	0.02–0.24	.698
Occlusal deviation, mm	0.12	0.09–0.21	0.21	0.07–0.34	0.16	0.05–0.21	.339
Cervical deviation, mm	0.08	0.04–0.13	0.08	0.04–0.14	0.08	0.01–0.16	.536
Digital waxing time, min	9.45	6.20–11.30	5.35	4.25–7.10	5.90	4.60–7.35	.001

[a]Kruskal-Wallis test ($P < .05$ was considered statistically significant).

Table 2 Descriptive Quantitative Data and Statistical Differences Among CAD Operator Groups of 3D-Printed Crowns

	Group ZZ-DENT		Group ZZ-PROS		Group ZZ		
Variable	Median	Range	Median	Range	Median	Range	P^a
Marginal gap, μm	140.39	77.64–237.55	122.38	56.08–184.69	113.91	54.66–152.14	.949
Internal gap, μm	109.08	23.73–228.25	109.08	23.73–228.25	161.29	101.18–198.22	.305
Proximal deviation, mm	0.12	0.07–0.29	0.13	0.03–0.16	0.17	0.02–0.24	.425
Occlusal deviation, mm	0.17	0.07–0.28	0.15	0.05–0.22	0.16	0.05–0.21	.725
Cervical deviation, mm	0.07	0.03–0.22	0.08	0.04–0.15	0.08	0.01–0.16	.836
Digital waxing time, min	11.40	8.70–16.45	13.25	9.10–16.20	5.90	4.60–7.35	.001

[a]Kruskal-Wallis test ($P < .05$ was considered statistically significant).

All crowns were then rescanned with the intraoral scanner (Trios 4) using the 360-degree scanning tool and exported as new STL files. All pairs of STL files of each crown (ie, virtual wax pattern and crown rescan) were imported to a 3D mesh analysis software (Inspect 2019, GOM), to be superimposed and compared for 3D deviation (trueness, measured in millimeters) within a 3D color map using the best-fit algorithm, following a previously described methodology.[5–8] Medians and ranges of 3D deviation values were obtained for proximal, occlusal, and cervical (at the coupling interface) surfaces used in the statistical analyses.

Digital microscopy was performed on all cemented crowns using a high-definition optical microscope (Axioscope 5, Zeiss). Prior to analysis, all specimens were mounted in acrylic resin (Vari-Set, MetPrep) and cross-sectioned at the midline in the buccolingual direction. Multiple quantitative linear measurements of marginal and internal adaptation (ie, marginal and internal gap measurements) were performed in random order. All measurements were digitally performed in microns with the manufacturer's software (AxioVision, Zeiss) in random order by two trained observers. To assess intraobserver reliability, both observers performed their measurements twice, at 2-week intervals, to eliminate memory bias.

For statistical analysis, the sample size was estimated to give the study a statistical power of 80% at a significance level of 5% using the Noether formula. Normality of all variables was assessed with Shapiro-Wilk test. Intra- and interobserver agreements of microscopic measurements were assessed with Wilcoxon signed-rank test for repeated measurements. Statistical differences in marginal and internal gaps; 3D deviation of proximal, occlusal, and cervical surfaces; interproximal contact scale; and time required for digitally designing among CAD software and CAD operator groups were assessed with Kruskal-Wallis test with post hoc Mann-Whitney test to address pairwise differences. All analyses were performed at a 5% level of significance using SPSS Statistics (version 28, IBM).

RESULTS

Normality of measurements were rejected for all variables ($P < .05$). Intra- and interobserver agreements for microscopic measurements were confirmed with Wilcoxon test results ($P > .05$). Quantitative descriptive and statistical results for CAD software and operator comparisons are available in Tables 1 and 2, respectively. No significant differences among test groups were found for variables assessed with microscopy or 3D deviation

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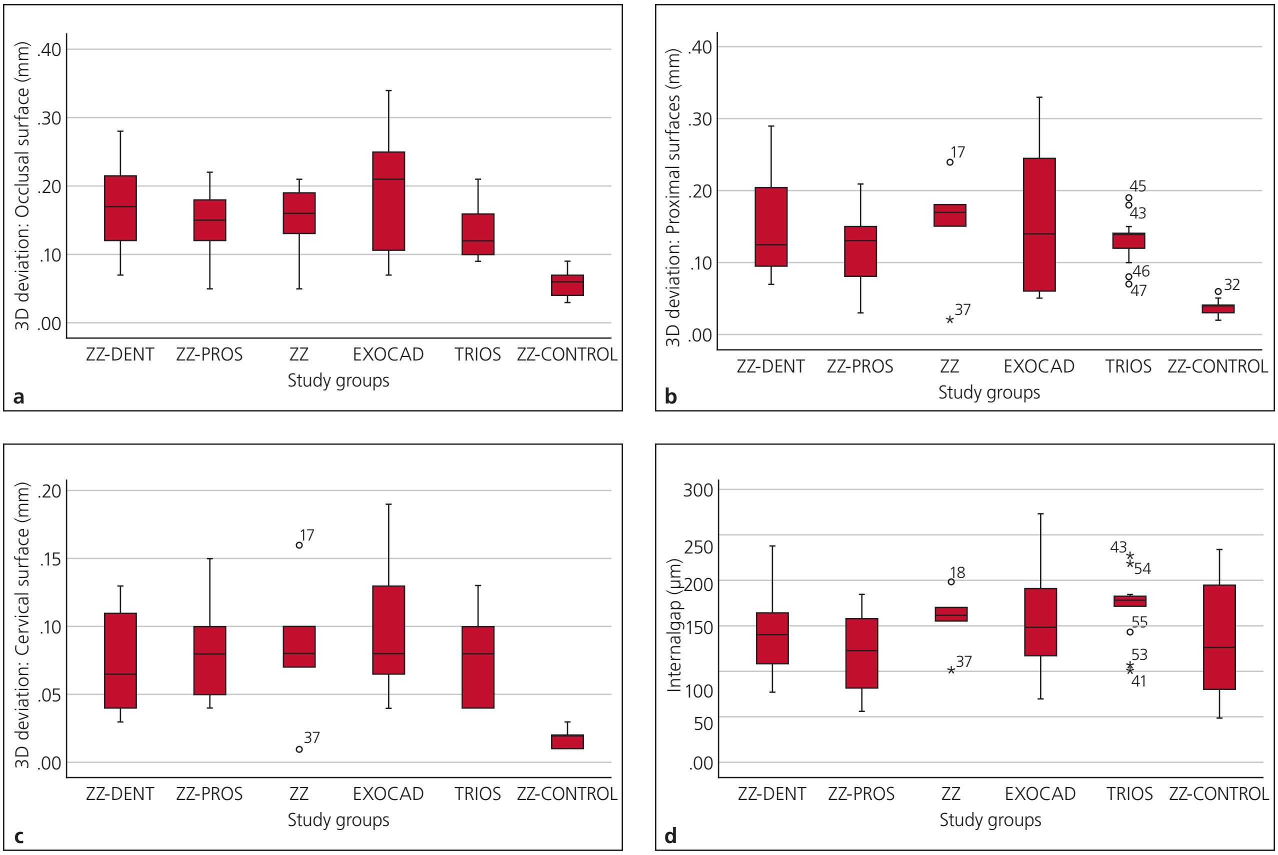
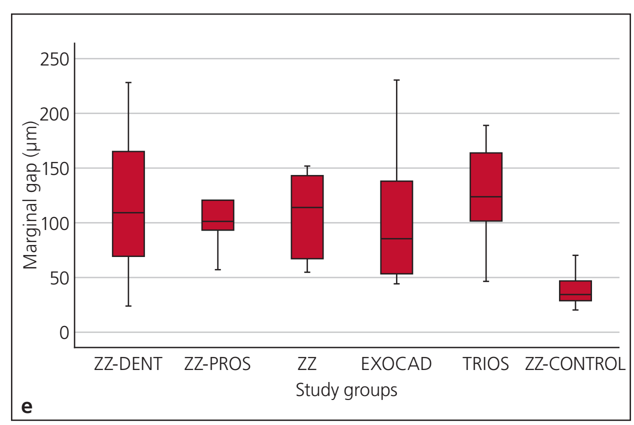


Fig 3 Group results for variables related to microscopy *(a and b)* and 3D trueness *(c to d)*.



(Fig 3). On the other hand, the control group (ZZ-CONTROL) had significantly smaller marginal gaps (Fig 4) and lower 3D deviations (Fig 5) for all surfaces analyzed ($P < .001$) than the respective 3D-printed copies (group ZZ).

The CAD technician took significantly longer to digitally design single crowns with Dental System (TRIOS) than with DentalCAD (EXOCAD) and Modellier (ZZ) ($P = .001$). Similarly, the CAD technician (ZZ) was significantly faster than both the dental clinician (ZZ-DENT) and dental prosthetic technician (ZZ-PROS) at digital design using the Modellier software. A pairwise significant difference revealed that the dental clinician was also faster than the dental prosthetic technician ($P = .012$).

Regarding interproximal contacts, there were no significant differences among CAD software programs ($P = .780$). None of the crowns designed by the CAD technician (TRIOS, EXOCAD, and ZZ) needed to be remade. Of these, only two crowns in the ZZ group needed chairside adjustments due to excessive interproximal contacts. On the other hand, the ZZ group significantly ($P = .001$) outperformed ZZ-DENT (8 out the 15 crowns needed to be remade due to lack of interproximal contacts, and 1 crown needed chairside adjustments)

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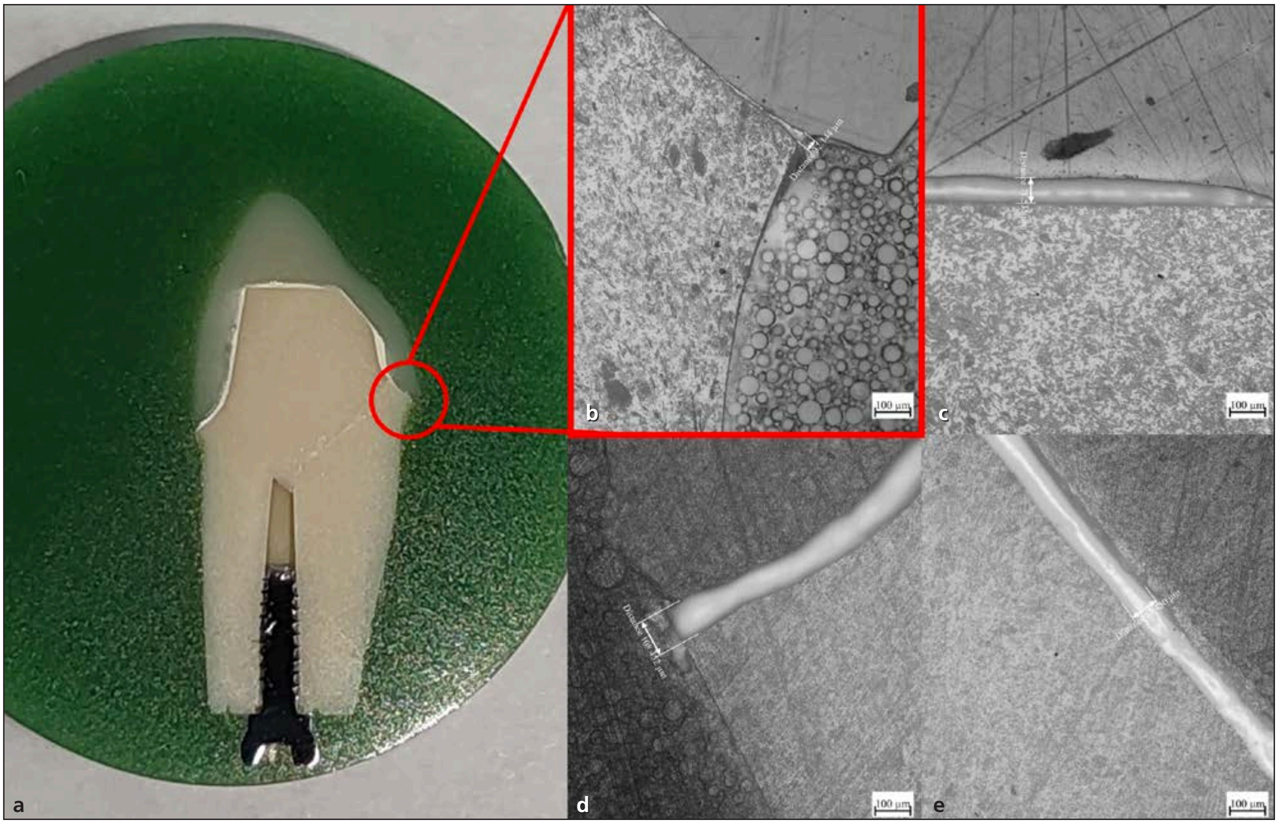

Fig 4 Digital optical microscopy results. *(a)* Setup for cross-sectional analysis. *(b)* Marginal gap from a milled crown in the ZZ-CONTROL group (magnification of *a*). *(c)* Internal gap from a milled crown in the ZZ-CONTROL group. *(d)* Marginal gap from a 3D-printed crown in the ZZ group. *(e)* Internal gap from a 3D-printed crown in the ZZ group.

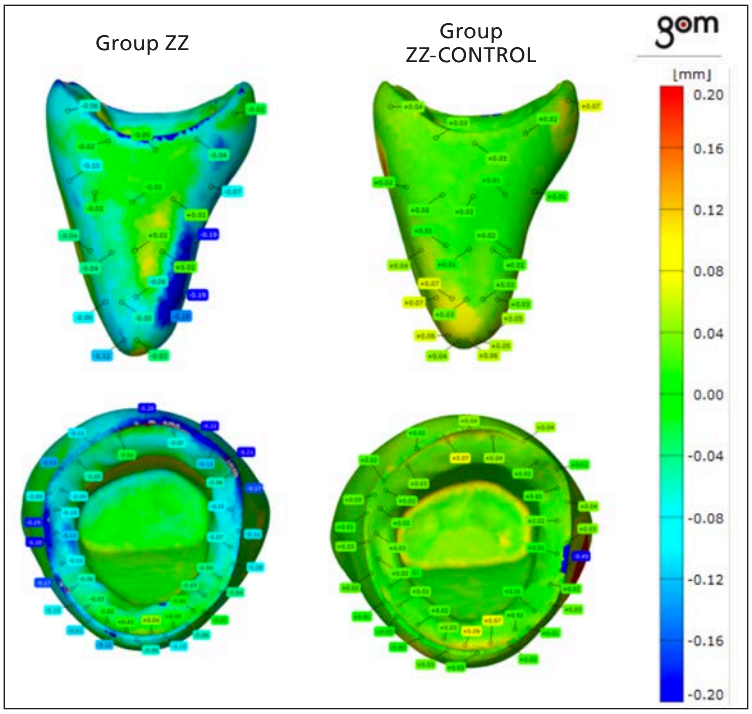

Fig 5 Mesh comparison output of 3D deviation measurements for mesial and cervical (internal margin at the coupling interface) surfaces. The milled crowns from the control group were significantly more accurate than the respective 3D-printed copies ($P < .001$).

and ZZ-PROS (10 of the 15 crowns needed to be remade) groups, with no significant pairwise difference between the latter two groups ($P = .228$). In addition, all crowns in the ZZ-CONTROL group had adequate fitting without needing chairside adjustments.

DISCUSSION

This in vitro study compared clinical outcomes of 3D-printed single crowns designed by different CAD software programs. There was no significant difference among groups for variables related to trueness (3D deviation) and adaptation (marginal and internal gaps). This finding agrees with previous CAD studies that did not find significant differences in trueness of digital designs of single crowns among operators with different backgrounds and using different software programs.[5,6]

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The only significant different among software programs was that group TRIOS was significantly slower to digitally design crowns. The explanation given by the CAD technician was that the interface of Dental System is different from the two other software programs (ie, slightly more complex to achieve the same tasks). On the other hand, this finding also suggests that the 3D-printing procedure does not significantly alter the shape of the single crown designed in CAD software programs, which is clinically relevant because excessive internal misfit may affect the success of CAD/CAM crowns.[11] Although there is currently no consensus on clinically acceptable thresholds for marginal and internal gaps, it has been suggested that marginal gaps up to 120 μm[12,13] and internal gaps up to 200 μm[14] are satisfactory. Therefore, the present CAD/CAM crown fit results were generally within the clinically acceptable range. These findings agree with previous studies showing satisfactory adaptation and trueness of 3D-printed and milled resin CAD/CAM crowns, with the latter showing better trueness.[8,15]

On the other hand, the present additional analysis of interoperator reproducibility revealed significant differences in time required for digital designing among operator groups. This supports previous evidence that professionals with more experience in CAD/CAM design a virtual crown significantly faster than dentists with basic CAD training.[5,6] Faster procedures lead to shorter chairside time at appointments and a shorter total treatment time, which is an important advantage of digital workflow in restorative dentistry.[16,17] However, it is noteworthy that the present inclusion of three operators addresses interoperator reproducibility but not the impact of different levels of expertise on the clinical outcomes of 3D-printed crowns. In turn, this impact is currently being investigated on a different project by the present group.

This is the first study on the influence of digital designs on interproximal contact points with adjacent teeth. According to the present results, a professional who is trained and experienced in both dental and CAD/CAM technology significantly outperforms dental clinicians and even dental prosthetic technicians with basic 1-week CAD training. This finding supports the importance of the learning curve required to avoid crown remakes and implement CAD/CAM technology in dentistry.[17]

Among the main limitations of this study is the in vitro design, which prevented the authors from addressing the impact of clinical factors that are known to affect trueness of CAD/CAM crowns (eg, saliva, nonstandardized preparations, and mouth opening limitations). All of the crowns in the present study were made with the same virtual setting for cement gap thickness (35 μm), whereas other values could have an influence on the final crown adaptation.[14] Moreover, the present CAD study does not address the impact of components related to the 3D printing procedure, such as different light-cured resins or orientations in the printing bed. Finally, only a low-cost LCD 3D printer was used, where more expensive DLP 3D printers could possibly lead to better results.[2,18] Therefore, future clinical studies should evaluate the effect of the different steps of CAD/CAM methodology on the accuracy and precision of digital designing procedures.

CONCLUSIONS

Within the limitations of this study, the present findings suggest that different CAD software programs may affect the time required to design single resin crowns produced with a low-cost LCD 3D printer. The results also suggest that low-cost 3D-printed crowns designed by a professional who is trained in both CAD/CAM and dental technology with more than 5 years of experience will likely not require chairside adjustments for adequate seating, regardless of the CAD software program used.

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