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Original Article

Effect of build orientation on the fracture resistance and marginal quality of 3D-printed anatomic provisional crowns: An in-vitro study

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ABSTRACT

Introduction: Computer-aided design and computer-aided manufacturing (CAD/CAM) technologies have been increasingly used to fabricate provisional restorations in recent years. This study assessed how build orientation influences the fracture resistance and marginal quality of 3D-printed crowns compared with milled provisional crowns.

Methods: The test group included 3D-printed crowns (Freeprint temp Shade A2, Detax, Ettlingen, Germany), which were further subdivided based on print orientation (0°, 45°, and 90°; n = 10 for each subgroup). The control group (n = 10) included milled crowns (Coratemp, White Peaks, Germany) with the same design as those of the test group. The margin quality of each crown was assessed at 60 × magnification using a digital stereo-microscope. A load-to-fracture test was performed by applying a force at a rate of 2 mm/min to assess fracture resistance. One sample from each subgroup was also subjected to scanning electron microscope (SEM) analysis.

Results: The milled group exhibited the highest fracture resistance and marginal quality. Within the printed subgroups, the 0° group showed the best mean marginal quality, whereas the 90° group showed the lowest mean marginal quality ($p < 0.05$). Within the test groups, the 90° group had the highest mean fracture resistance ($p < 0.05$). In the SEM analysis, the milled group exhibited the most homogenous boundaries, whereas among the 3D-printed subgroups, the samples printed at 0° had the best margin quality.

Conclusion: The manufacturing method significantly influences the marginal quality and fracture resistance. Milled crowns demonstrated superior marginal quality and fracture resistance compared to those of 3D printed crowns. Furthermore, the print orientation of 0° led to the best marginal quality, whereas printing at 90° led to the highest fracture resistance.

1. Introduction

In fixed prosthodontics, interim restorations play an essential role in preserving gingival health and contours (Martín-Ortega et al., 2022). They also contribute to shielding the pulp from thermal damage, stabilizing the underlying abutments, and allowing for an accurate assessment of esthetics and occlusion before definitive restorations (Henderson et al., 2022, Martín-Ortega et al., 2022). Recent advances in digital technologies have led to the increased utilization of computer-aided design and computer-aided manufacturing (CAD/CAM) in fabricating provisional restorations (Alharbi et al., 2016, Shim et al., 2020, Valenti et al., 2022).

Computer aided manufacturing involves either additive or subtractive manufacturing (Henderson et al., 2022). Subtractive manufacturing involves the controlled removal of material from a solid block in three dimensions to form the desired product. In contrast, additive manufacturing works by adding successive layers of material to achieve the final outcome (Berman, 2012, Alharbi et al., 2016, de Oliveira Limírio et al., 2022). Additive manufacturing in dentistry involves digital light processing, stereolithography, selective laser melting, and selective laser sintering (Alharbi et al., 2016). The choice of the manufacturing method depends on the material's characteristics, cost,

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Fig. 1. Additive manufacturing samples positioned at their relative orientations on the printing platform immediately after printing using temporary crown and bridge material (Freeprint temp, Detax Ettlingen, Germany).

and the desired quality (Alharbi et al., 2016, Gad and Fouda, 2023).

Several studies have reported that milled restorations show superior mechanical properties and surface characteristics compared to those of printed restorations (Çakmak et al., 2022, Henderson et al., 2022, Martín-Ortega et al., 2022, Valenti et al., 2022, Jang et al., 2023). However, 3D printing is more cost-effective as it produces less material waste (Rekow, 2020, Çakmak et al., 2021, Tian et al., 2021, Valenti et al., 2022, Gad and Fouda, 2023). Additionally, vertical manufacturing through printing methods allows the creation of more complex structures (Çakmak et al., 2021, Valenti et al., 2022, Gad and Fouda, 2023).

During 3D-printing of provisional restorations, various parameters can influence the final outcome. These include print layer thickness, light or laser intensity and speed, printing orientation, material choice, printing technology, and post-processing protocols (Alharbi et al., 2016). Successful 3D printing relies on selecting the appropriate settings for each of these parameters because they significantly affect printing accuracy and mechanical characteristics (Park et al., 2019).

While the effects of build orientation and print layer thickness have been previously reported, limited data is available on their effects when applied to fully anatomical provisional crowns (Alharbi et al., 2016, Park et al., 2019, Çakmak et al., 2021, Yu et al., 2021, Çakmak et al., 2022, Diken Turksayar et al., 2022, Jang et al., 2023). Furthermore, studies assessing these parameters have mainly focused on 3D printing of posterior provisional crowns or fixed partial dentures (Park et al., 2019, Çakmak et al., 2021, Çakmak et al., 2022, Diken Turksayar et al., 2022, Jang et al., 2023).

This study aimed to assess the influence of build orientation on the fracture resistance and marginal quality of anatomically shaped 3D-printed anterior provisional crowns in comparison with milled provisional crowns. The null hypothesis was that the build orientation would have no effect on the fracture resistance and marginal quality of 3D printed anterior provisional crowns.

2. Materials and methods

A test die was cast from chromium-cobalt metal and meticulously shaped to create an anatomical crown. mm, a smooth and consistent, 1-mm wide, deep chamfer finish line, 2 mm of incisal reduction, uniform axial reduction of 1.5 mm, a 4-mm preparation height, and an axial taper angle of 10°. The metallic test die was scanned using an extraoral scanner (Ceramill Map 600 + GmbH). The surface scan was then converted into a standard tesselation language (STL) file, which was subsequently imported into the dental design software (Exocad v3.0, Ceramill Mind, GmbH). Using the software, a digital design for a fully contoured anatomical crown was created, including 50 µm of cement space beginning 1 mm coronal to the preparation margin and maintaining a minimal thickness of 1 mm for the crown at all cross-sections. After the design was finalized, the resulting STL file was exported to the manufacturing process.

Test group samples were printed using nesting software (Asiga Composer, Asiga, Australia). The samples were divided into three subgroups each with a distinct print orientation (0°, 45°, and 90°). Initially, the position of 0° was established by aligning the lingual surface of the crown parallel to the platform. Automated supports were generated and this orientation was duplicated 10 times. Next, the position was adjusted to 45°, with automated supports generated and duplicated 10 times. Finally, a 90° position was set to orient the incisal edge toward the platform. Automated supports were generated and the final position was duplicated 10 times. A digital light-processing 3D printer (Asiga Max, Asiga, Australia) was used to print all samples. A 50-µm print layer thickness was maintained for all samples, utilizing the same temporary crown and bridge 3D printing resin material (Freeprint temp Shade A2, Detax Ettlingen, Germany).

Ten samples were printed for each subgroup as previously reported (Fig. 1) (Shim et al., 2020, Çakmak et al., 2021, Çakmak et al., 2022, Donmez and Okutan, 2022, Martín-Ortega et al., 2022, Al-Dulaijan et al., 2023, Scherer et al., 2023). Postprocessing was performed according to the manufacturer's instructions. This involved a drip time of 10 min, followed by two cycles of cleaning in isopropyl alcohol of 98 % purity in an ultrasonic bath for 3 min. A post-curing unit (Asiga Flash Cure Box, Asiga, Australia) was used for 3 min to obtain the final mechanical properties. Sharp scissors were used to cut the support structures 2–3 mm away from the crown surface. The remaining projections were lightly polished using a fine fluted carbide bur at low speed with a gentle brushing motion under 3.5x magnification using dental loupes.

For the control group, a 5-axis milling machine (Ceramill 3 motion, GmbH, Germany) was used to mill 10 samples from a polymethyl methacrylate block (Coratemp, White Peaks, Germany), employing the same crown design STL file.

To ensure the absence of defects prior to testing, a single operator meticulously examined the crowns under 3.5 × magnification using dental loupes. Thirty printed and ten milled samples were used in this study.

Before testing, an independent researcher assigned random numbers

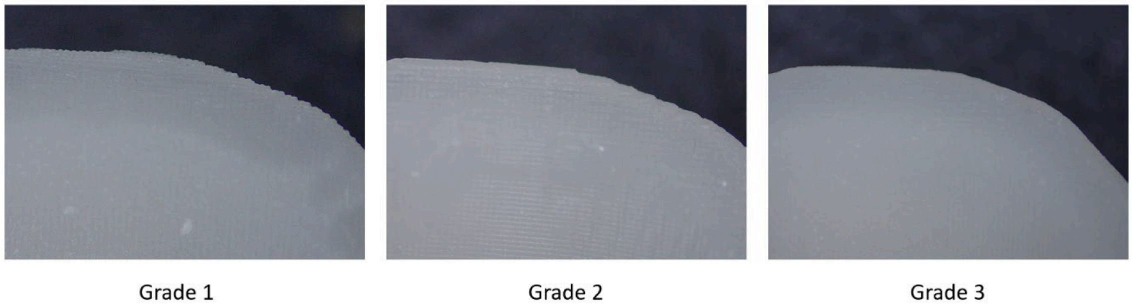

Fig. 2. Margin quality grading system. Grade 1: rough boundaries appearing as steps or layers. Grade 2: slightly rough boundaries with fewer irregularities. Grade 3: smooth and continuous boundaries.

Table 1
Descriptive statistics of the study samples.

Variables	N	Min.	Max.	Mean	SD	Median
Fracture resistance						
90°	10	313.90	473.50	397.28	49.8	398.40
45°	10	271.20	366.60	321.13	30.6	317.20
0°	10	312.00	455.60	374.99	39.7	369.20
Milled	10	1049.60	1257.00	1157.16	75.0	1186.65
Margin quality						
90°	10	1.00	2.00	1.60	0.5	2.00
45°	10	1.00	2.00	1.80	0.4	2.00
0°	10	2.00	3.00	2.50	0.5	2.50
Milled	10	3.00	3.00	3.00	0.0	3.00

to each crown. Subsequently, an operator who was uninformed about the numbering sequence received each crown individually. Using a digital stereomicroscope (RaySmart Technology Co., Ltd., Shenzhen, China) set to 60 × magnification, the operator assessed the margin quality in the buccal region of each crown. The evaluation was randomized. Each crown was rated on a scale of 1 to 3, with Grade 1 denoting roughened borders resembling layers or steps, Grade 2 signifying slightly rough boundaries with fewer irregularities, and Grade 3 denoting smooth and continuous margins (Fig. 2).

To prepare each sample for the fracture resistance test, it was cemented onto a chromium-cobalt test die using a zinc oxide non-eugenol temporary cement (RelyX Temp NE, 3 M, MN, USA). To simulate the intraoral conditions of the anterior teeth, the crown and die were set at an angle of 30° relative to the applied force. A universal testing device (Mecmesin 2.5-I, PPT Group UK Ltd., United Kingdom) was used to conduct the load-to-fracture tests. This involved the use of a cone-shaped insert and application of a force at a rate of 2 mm/min. All fracture-to-load tests were performed by the same operator. For each group, the maximum fracture value was recorded in Newtons (N).

An additional visual analysis was conducted on one sample from each subgroup using a scanning electron microscope (SEM; AURA100 SEM, Seron Technologies Inc., Korea). Prior to SEM imaging, a high-vacuum sputter coater (Q150 V Plus, Quorom Tech., United Kingdom) was used to enhance conductivity. SEM imaging was performed at 45 ×, 90 ×, 190 ×, and 300 × magnifications for each sample.

All the statistical analyses were performed using SPSS version 27 (IBM Corp., Armonk, NY, USA). Descriptive statistics (mean and standard deviation) were used to describe the characteristics of the study variables. To examine the relationship between more than two mean groups, a one-way ANOVA was employed, with Games-Howell as the post-hoc test. The homogeneity of variance was assessed using Levene's test. The criterion for rejecting the null hypothesis was set at $p < 0.05$.

3. Results

Descriptive statistics for the study sample are presented in Table 1.

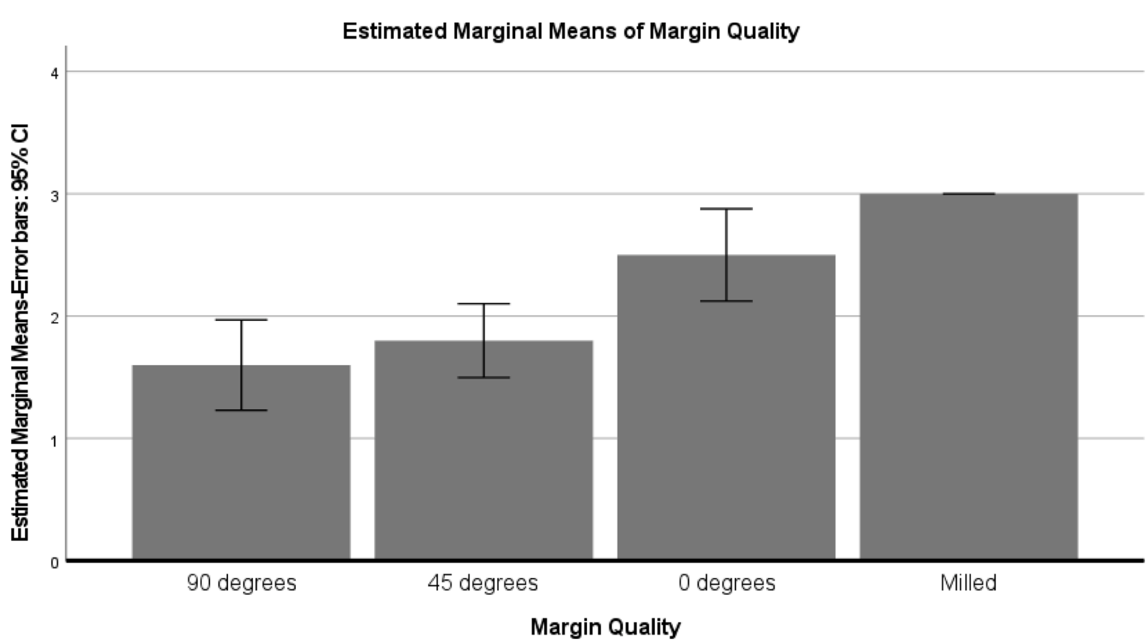

Fig. 3. Graphic illustration of estimated marginal means of margin quality scores.

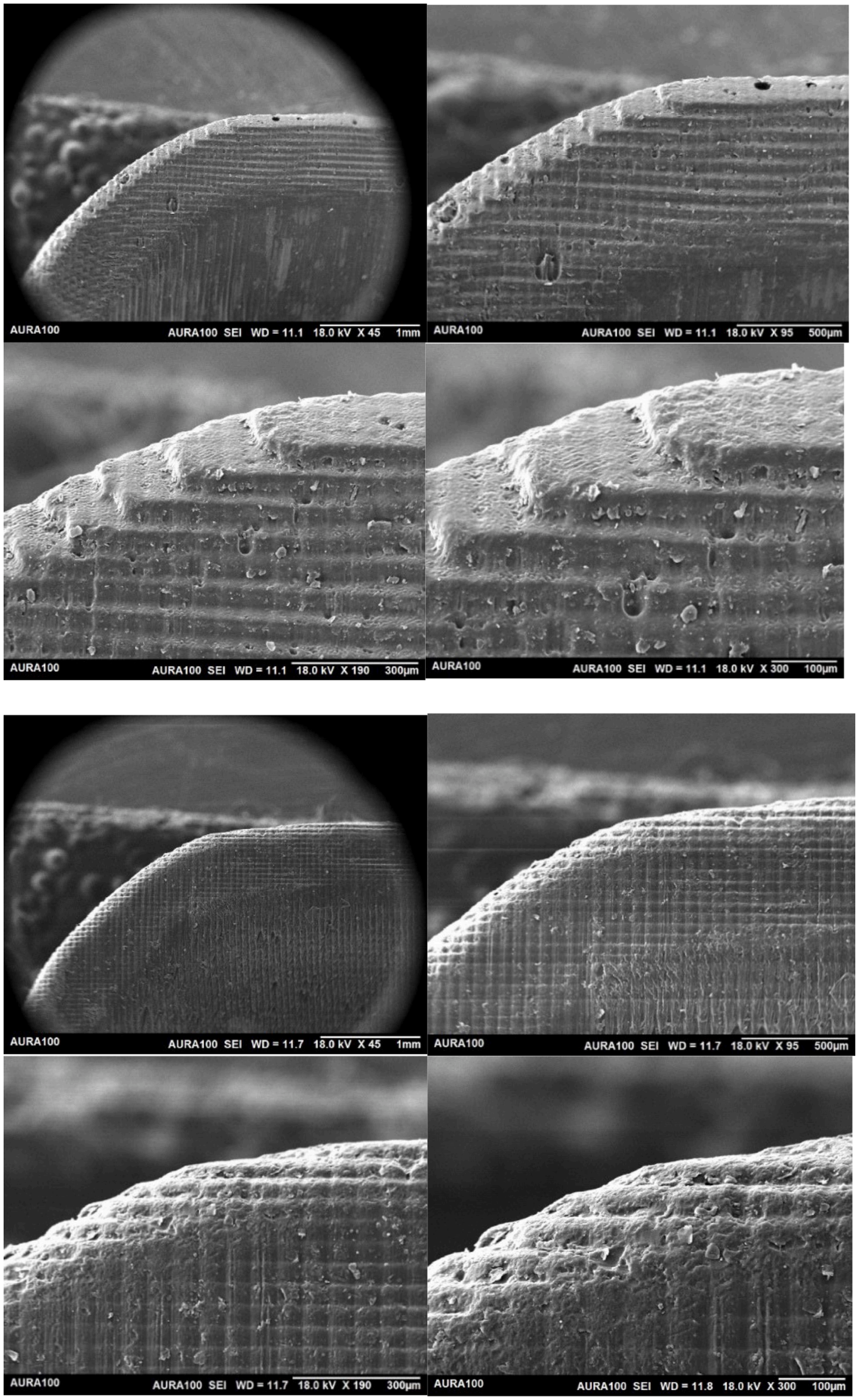

Fig. 4. SEM images of crown margins 3D printed at 90° (Top 4 images), 45° (middle 4 images), and 0° (bottom 4 images) at different magnifications. From left to right: 45×, 95×, 190×, and 300 × magnification.

Overall, the milled group exhibited the best marginal quality and the most consistent outcomes (3). Within the additive manufacturing subgroups, the 0° group showed the best mean marginal quality score of 2.5, followed by the 45° group, with a score of 1.8. The samples printed at 90° had the lowest mean marginal quality score (1.6).

The milled group exhibited a higher overall mean fracture resistance (1157.17 ± 75.04 N). Within the additive manufacturing subgroups, the 90° group had the highest mean fracture resistance (397.28 ± 49.79 N) while the 45° group showed the lowest fracture resistance (321.12 ± 30.64 N).

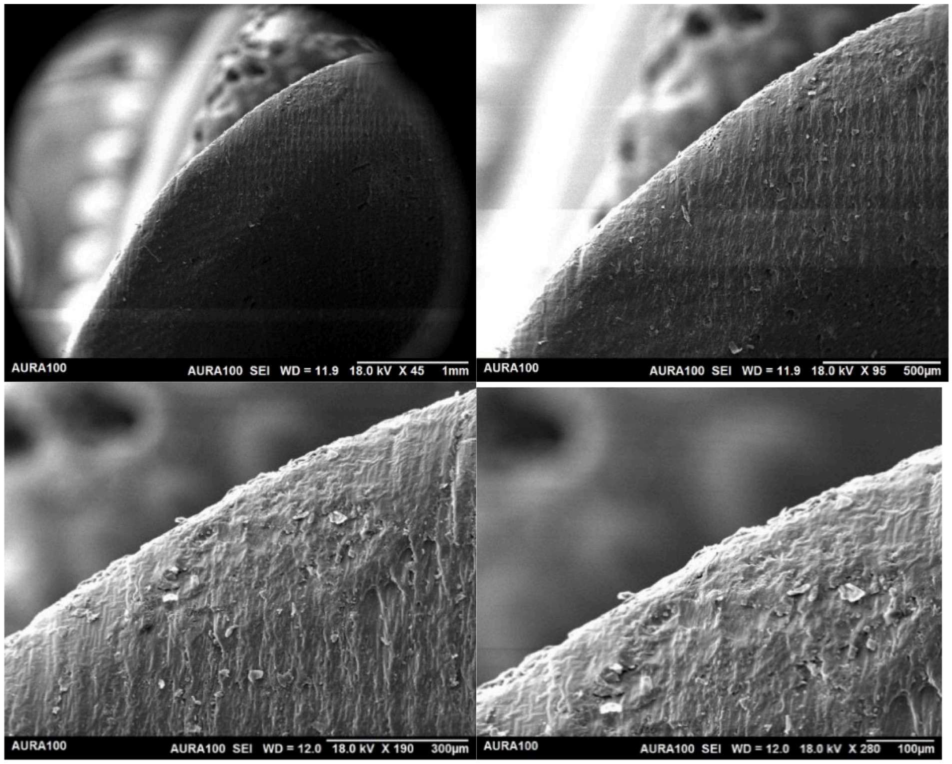

Fig. 4. (*continued*).

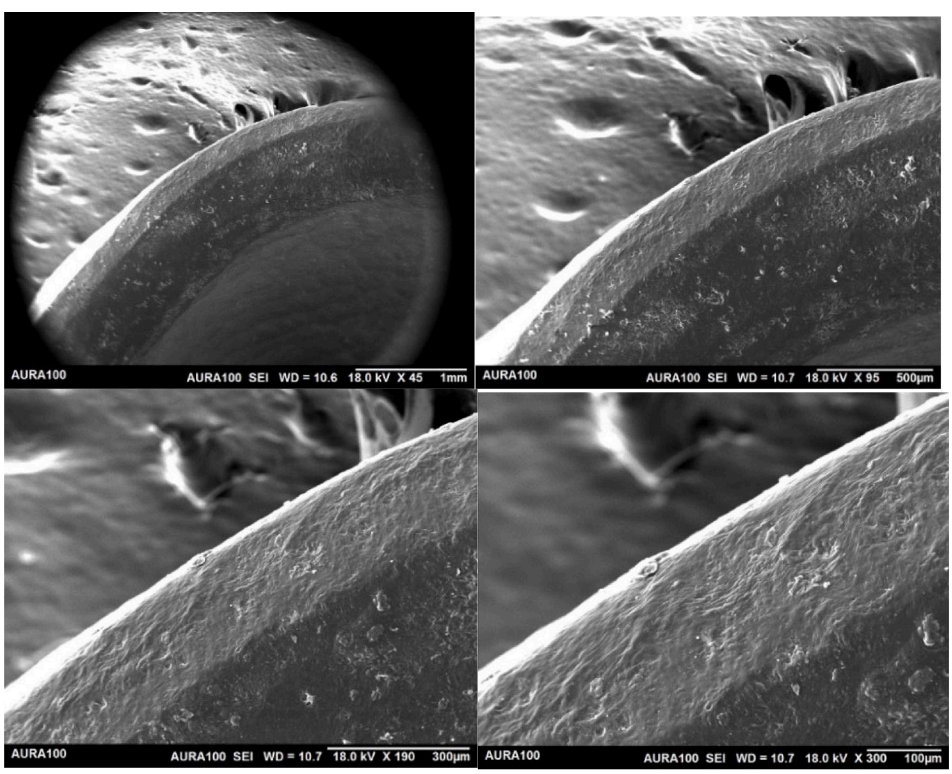

Fig. 5. SEM images of crown margins milled at different magnifications. From left to right: 45×, 95×, 190×, and 300 × magnification.

One-way ANOVA revealed significant differences in fracture resistance between the groups ($p < 0.05$). The milled samples had significantly higher fracture resistance values than those exhibited by the additive manufacturing subgroups. Within the additive manufacturing subgroups, samples printed at 45° had significantly lower fracture resistance than those of samples printed at 90° and 0°.

For marginal quality, a one-way ANOVA revealed significant differences between the groups ($p < 0.05$). The milled group had significantly higher scores than those of the 45° and 90° subgroups. However, no significant differences were observed between the 0° and milled groups. Within the additive manufacturing subgroups, samples printed at 0° significantly outperformed those printed at 90° in terms of the marginal quality (Fig. 3).

Figs. 4 and 5 show SEM images of each subgroup. The milled group exhibited the most homogenous and smooth boundaries with the least number of obvious defects. A layered or wavy appearance was a consistent feature of the additive manufacturing subgroups at all magnifications. All printed crowns displayed small particles of adherent resin at higher magnifications (190–300x). Among the additive manufacturing subgroups, the sample printed horizontally at 0° exhibited the best margin quality and surface characteristics. This group displayed the most uniform surface with the least appreciable demarcation between the layers, which most closely resembled the milled crowns. The subgroup printed at 90° had the least favorable surface topography, with rough edges and step-like external borders. This group also displayed areas of incomplete manufacturing, resulting in clearly demarcated voids on the intaglio surface and margin area. Finally, the 45° subgroup displayed a weave-like pattern and appreciable demarcation between the print layers as well as areas of incomplete manufacturing, resulting in minimal voids on the surface intaglio.

4. Discussion

Based on the results of this study, the choice of manufacturing method significantly influences the mechanical and surface properties of CAD/CAM restorations. The subtractive manufacturing technique yielded the best mechanical properties and the most consistent results when compared with those of additive manufacturing techniques.

Within the additive manufacturing subgroups, the build orientation had a notable impact on both the mechanical properties and marginal quality of the 3D-printed anatomical anterior provisional crowns, which led the authors to reject the null hypothesis. The 90° build orientation, which involved printing the crowns vertically, exhibited the highest fracture resistance. Conversely, the 0° build orientation with horizontally printed crowns displayed the best marginal quality when assessed under a light microscope and SEM.

In terms of mechanical testing, significantly higher fracture resistance was observed in the milling group than in the 3D printing groups. These results may be attributed to the highly cross-linked nature of the preprocessed acrylic blocks, which were fabricated under high pressure, resulting in a dense, nonporous structure (Henderson et al., 2022). Notably, all samples demonstrated clinically acceptable fracture load values ranging from approximately 300 to 1,000 N, which is well within the typical range for anterior crowns, where forces typically range from 50 to 250 N (Martín-Ortega et al., 2022).

Previous studies have reported similar findings regarding the influence of build orientation on the mechanical properties of 3D printed resins. Al Harbi et al. demonstrated that vertically printed cylindrical resin specimens exhibited significantly higher compressive strengths than those exhibited by horizontally printed specimens (Alharbi et al., 2016). Shim and Dulaijan supported these findings, indicating that samples printed horizontally at 0° had a higher three-point flexural strength than that of samples printed vertically at 90° (Shim et al., 2020, Al-Dulaijan et al., 2023).

Regarding marginal quality assessment, the present study found that a 90° print orientation yielded the least desirable outcomes. This might have been related to the curved nature of the anatomic crown margins, leading to an unfavorable layer orientation at the outer periphery when printed vertically. The optimal margin quality among the additive manufacturing subgroups was observed in the samples printed horizontally at 0°, where the layer orientation appeared to blend more homogeneously, resulting in a continuously smooth boundary under both light and scanning electron microscopy.

The findings of this study also confirmed the impact of build orientation on the marginal quality of 3D-printed crowns using SEM analysis. Under all SEM magnifications, the milled crowns exhibited superior visual marginal quality compared to those exhibited by the 3D-printed subgroups. Within the 3D printing subgroups, horizontally printed crowns displayed the most continuous and homogeneous outlines, whereas vertically printed crowns exhibited the most irregular and non-homogeneous margins.

A limitation of this study was its *in vitro* design, which may limit the applicability of its results in clinical settings. Other limitations include the lack of fractographic analysis, the limited sample size, and the limited number of tested materials. Further *in vitro* trials with larger sample sizes and clinical studies are required to reach a scientific consensus on the effects of different variables on the properties of 3D-printed resins.

5. Conclusions

Among the various manufacturing techniques evaluated, the milled group exhibited the most favorable outcomes, demonstrating superior marginal quality and fracture resistance.

Within the additive manufacturing subgroups, crowns printed at 45° had significantly lower fracture resistance values, whereas those printed at 0° performed the best with respect to marginal quality.

Therefore, for 3D-printed provisional crowns, it may be advantageous to use print angles of 0° or 90°. Further studies are required to reach a scientific consensus on the best print orientation for the overall performance of provisional anterior crowns.

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Authors Contribution

Abdulrahman Aljehani: concept, design, definition of intellectual content, literature search, data acquisition manuscript preparation, guarantor. Abdulmajeed Nabalawi: concept, design, definition of intellectual content, literature search, data acquisition manuscript preparation, guarantor. Ahmed Hefni: concept, design, definition of intellectual content, literature search, data acquisition manuscript preparation, guarantor. Ziyad Alsefri: concept, design, definition of intellectual content, literature review, data acquisition manuscript preparation, guarantor. Omar Fakhry: concept, design, definition of intellectual content, literature review, data acquisition manuscript preparation, guarantor. Walaa Al Zaibak: concept, design, definition of intellectual content, data analysis, manuscript preparation, manuscript editing and manuscript review, guarantor. Ossama Raffa concept, design, definition of intellectual content, data analysis, manuscript preparation, manuscript editing and manuscript review, guarantor.

I declare that I participated in the design, execution, and analysis of the paper by Abdulrahman Aljehani and colleagues, entitled:

"Effect of build orientation on the fracture resistance and marginal quality of 3D-printed anatomic provisional crowns: An in-vitro study", that I have seen and approved the final version of the paper and that it has neither been published nor submitted elsewhere.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sdentj.2024.01.004.

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