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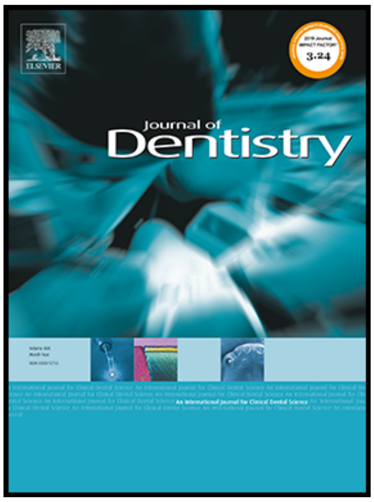

Effect of printing orientation on the fracture strength of additively manufactured 3-unit interim fixed dental prostheses after aging

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Effect of printing orientation on the fracture strength of additively manufactured 3-unit interim fixed dental prostheses after aging

Original article

Full Title: Effect of printing orientation on the fracture strength of additively manufactured 3-unit interim fixed dental prostheses after aging

Short title: Fracture strength of interim bridges

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Keywords: Fracture strength, interim restoration, printing orientation, thermomechanical aging

HIGHLIGHTS

- Printing orientation affects the fracture strength of 3D-printed interim fixed partial dentures.
- Fabrication method does not affect the failure type of interim fixed partial dentures.

ABSTRACT

Objectives: To evaluate the effect of printing orientation on the fracture strength of 3-unit interim fixed dental prostheses fabricated by using additive manufacturing and to compare with those fabricated by subtractive manufacturing after thermomechanical aging.

Materials and Methods: A 3-unit fixed dental prosthesis was designed by using a dental design software (exocad DentalCAD 2.2 Valetta) in standard tessellation language (STL) format. This STL file was exported into a nesting software (PreForm) and 3-unit interim fixed dental prostheses with 5 different orientations (0°, 30°, 45°, 90°, and 150°) were printed by using a 3-dimensional (3D) printing interim resin (Temporary CB) (n=10). The same STL file was also used to mill polymethymethacrylate (DuoCAD) 3-unit interim fixed dental prostheses as the control group (n=10). All specimens were cemented onto cobalt-chromium test models representing a maxillary first premolar and first molar tooth with a long-term temporary cement (DentoTemp), and subjected to thermomechanical aging (120000 cycles, 1.6 Hz, 50 N, 5-55°C). Then, all specimens were loaded until fracture by using a universal tester. The data were analyzed with nonparametric 1-way analysis of variance (Kruskal-Wallis) and Dunn's tests ($\alpha = 0.05$).

Results: Additively manufactured specimens printed with 90° showed the lowest fracture strength values (*P*≤.048). However, the difference between specimens printed with 45° and 90° was nonsignificant (P>.05). Milled 3-unit interim fixed dental prostheses withstood significantly higher loads than 3-unit interim fixed dental prostheses printed with 45° and 150° (*P*≤.012). In addition, specimens printed with 0° showed higher fracture strength than the specimens printed with 45° (*P*=.01). Specimens printed with 0° and 30° presented similar fracture strength values with milled (*P*≥.057) and 150° printed (*P*>.05) specimens.

Conclusion: Printing orientation had a significant effect on the fracture strength of 3-unit interim fixed dental prostheses. Among the additively manufactured samples, those printed with 0° showed similar fracture strength values with the subtractively manufactured samples.

Clinical Significance

Three-unit interim fixed dental prostheses fabricated with 0° and 30° using the 3D printing interim resin tested may be alternatives to milled PMMA in terms of fracture strength.

1. INTRODUCTION

A critical step in fixed prosthodontic treatment is interim restorations [1, 2]. These restorations provide an esthetic solution, function, and protection by replacing the missing tooth structure [3, 4]. Indirect fabrication of these restorations with computer aided design-computer aided manufacturing (CAD-CAM) technologies is reasonable given the shortcomings of direct fabrication [5]. Even though the clinical use of interim restorations is limited to a certain amount of time, they should be able to resist intraoral repetitive forces and temperature changes, regardless of the fabrication method [6].

CAD-CAM technologies have been well-integrated into dentistry as fabricated restorations have higher precision and efficiency [7, 8]. After data acquisition and restoration design, the manufacturing stage is completed either with additive or subtractive methods [9]. Additive manufacturing or 3-dimenstional (3D) printing enables manufacturing of free-form objects with less waste material and has increased its popularity in dentistry with increased accuracy and speed of fabrication [10, 11]. The American Section of the International Association for Testing Materials International Standard Organization has categorized additive manufacturing techniques as stereolithography (SLA), digital light processing, material jetting, material extrusion, binder jetting, powder bed fusion, sheet lamination, and direct energy deposition [12]. SLA is the most commonly used vat-polymerization method in dentistry [13] and this technique is based on the polymerization of a light sensitive liquid resin with an ultraviolet laser [14, 15].

The manufacturing quality of additive methods depends on several factors such as printing layer thickness, laser intensity, and laser speed [16]. However, printing orientation emerges as a key factor considering the anisotropic behavior of the fabricated product depends on the printing direction [16, 17]. Even though previous studies have focused on the fracture strength of additively manufactured restorations [1, 3, 4, 7, 18-25], the number of studies on the effect of printing orientation on the fracture strength of fixed dental prostheses is limited [3, 20, 25]. In addition, none of those studies [3, 20, 25] have investigated the effect of changing the angle between the build platform and the restoration on fracture strength values. Therefore, the current study aimed to evaluate the effect of printing orientation on the fracture strength of 3-unit interim fixed dental prostheses after thermomechanical aging and to compare with those manufactured by milling. The null hypothesis was that there would not be any difference in the fracture strength of 3-unit interim fixed dental prostheses depending on manufacturing technique or printing orientation.

2. MATERIALS AND METHODS

A test model design simulating a maxillary first premolar and first molar tooth for a 3-unit fixed dental prosthesis was generated in standard tessellation language (STL) format by using a design software (Autocad; Autocad Inc.) based on a previous study [21]. The parameters of the 6° tapered cylindrical abutments were 5.4 mm in height, 6 mm (premolar) and 7.4 mm (molar) in width, and 0.8 mm-thick chamfer margin (Figure 1). This STL file was then transferred to a dental design software (exocad DentalCAD 2.2 Valetta; exocad GmbH) and a 3-unit interim fixed dental prosthesis was designed in STL format. The designed 3-unit interim fixed dental prosthesis had a 50 µm of cement space, 16 mm^2 of connector size, and a minimum occlusal thickness of 1.5 mm. Cobalt-chromium models were fabricated by using the model STL file through selective laser sintering (HBD-150; HBD) (Figure 1).

For the fabrication of additively manufactured specimens, STL file of the 3-unit interim fixed dental prosthesis was transferred into a nesting software (PreForm; Formlabs). The manufacturer of the 3D printing interim resin material (Temporary CB; Formlabs) recommends orienting restorations horizontally with the occlusal surface facing the build platform [22]. This position was set as 0°, duplicated 10 times for identical 3-unit interim fixed dental prostheses to be arranged, and saved as the master nesting file. Other additively manufactured specimens were also printed by using this master file after changing the angle between the occlusal surface of the 3-unit interim fixed dental prosthesis and the build platform (30°, 45°, 90°, and 150°) (Figure 2). Each group of additively manufactured specimens were printed at once. Supports were placed automatically and the thickness was set at 50 µm. Three-unit interim fixed dental prostheses were printed by using an SLA-based 3D printer (Form 3; Formlabs) and the printer was calibrated before each group as per manufacturer's recommendations. After printing, 3-unit interim fixed dental prostheses were placed in a bath (Form Wash; Formlabs) containing isopropyl alcohol and washed for 3 minutes. Any uncured resin residues were further removed with an isopropyl alcohol soaked brush. Three-unit interim fixed dental prostheses were then air-dried, removed from the build platform, and placed in a curing unit (Form Cure; Formlabs) for 20 min at 60°C. After first post-curing step, supports were removed by a single experienced dental technician. Specimens were then placed in the curing unit for an additional 20 min at 60°C with occlusal surfaces facing upwards. For the fabrication of subtractively manufactured specimens, STL file of the 3-unit interim fixed dental prosthesis was inserted into a PMMA disc (DuoCAD; FSM Dental) 10 times and milled by using a milling unit (CEREC MC X5; Dentsply Sirona). Supports were removed by the same dental technician. All 3-unit interim fixed dental prostheses were checked by using an optical magnification loupe (3.5×) to ensure that there were no defects. No additional polishing or glazing was performed [2-4, 20, 25].

Intaglio surfaces of all specimens and abutments were sandblasted by using 50 µm aluminum oxide. Abutment surfaces were then treated with a primer (Alloy Primer; Kuraray Dental) and 3-unit interim fixed dental prostheses were cemented onto their respective models by using a eugenol-free long-term temporary cement (DentoTemp; ITENA). After 24 h, the specimens were subjected to the dynamic loading and thermal stress in distilled water for 120000 cycles (1.6 Hz, 50 N, 5-55°C) by using a dual-axis chewing simulator (CS-4.4; SD Mechatronik), which reflects a clinical period of approximately 6 months [3]. The load was applied to the central fossa of the second premolar during aging and specimens were controlled twice a day for failure. All specimens survived the thermomechanical aging and further subjected to load-to-fracture test by using a universal testing machine (AGS-X; Shimadzu Corporation), where the force was applied to the central fossa of the second premolar perpendicularly at a speed of 1 mm/min with a 4 mm-diameter stainless steel ball. For the equal distribution of forces, 0.5 mm-thick aluminum foil was placed between the specimens and the steel ball [20]. Same operator (E.D.) performed all fracture-to-load tests. Maximum fracture values were recorded in Newton (N) for each group. The failure types were also evaluated by using a stereomicroscope (Nexius Zoom; Euromex) under 12.5× magnification and categorized as crack or fracture (connector, pontic, and retainer).

The number of specimens in each group (n=10) was decided based on a priori power analysis with 95% confidence (1-α), 95% test power (1-β), and f=1.021 effect size. Normality of the data was evaluated by using Shapiro-Wilk test. Due to the non-normal distribution, nonparametric 1-way analysis of variance (Kruskal-Wallis) test followed by Dunn's test were performed for the statistical analysis of the data by using a software (SPSS v23; IBM). Failure types were further evaluated by using Chi-square test ($\alpha = 0.05$).

3. RESULTS

Table 1 lists the descriptive statistics of the fracture strength of each group. Nonparametric 1-way analysis of variance (Kruskal-Wallis) test revealed significant differences among test groups ($P<.001$). Milled interim fixed dental prostheses showed higher fracture strength values than those of printed with 45° ($P<.001$) and 150° ($P=.012$), whereas the differences between milled, 0°, and 30° specimens were nonsignificant ($P\geq.057$). Specimens printed with 0° showed higher fracture strength values than the specimens printed with 45° ($P=.01$). However, no significant differences were observed between the specimens printed with 0°, 30°, and 150° ($P>.05$). Interim fixed dental prostheses printed with 90° presented significantly lower fracture strength values than the other specimens ($P\leq.048$), while the differences between the specimens printed with 45° showed similar values to those printed with 30°, 90°, and 150° (P≥.487) (Figure 3). Chi-square test revealed that the differences among test groups were nonsignificant ($P=.791$). Table 2 presents the number of crack or fracture incidents observed after load-to-failure test, while Figure 4 shows samples of different failure types.

4. DISCUSSION

The present study evaluated the fracture strength of 3-unit interim fixed dental prostheses fabricated by using additive and subtractive methods, after thermomechanical aging. Significant differences were found among the 3-unit interim fixed dental prostheses with different printing orientations and manufacturing methods. Therefore, the null hypothesis was rejected.

No significant differences were found among the 3-unit fixed dental prostheses printed according to manufacturer's recommendations (occlusal surface facing the build platform, 0°)

and those printed with 30° and 150°. However, 3-unit interim fixed dental prostheses printed with 90° showed significantly lower fracture strength than those printed with 0°. These results substantiate the findings of previous studies [11, 25] and may be explained by the fact that changing the printing orientation from 0° to 90° gradually positions the printed layers from perpendicular to parallel with respect to the build platform [11]. This may have led to a higher intra-layer strength compared with the inter-layer strength [11] and to a deterioration of the adhesion between layers [20, 25]. However, Park et al [25] also concluded that the difference between 3-unit interim fixed dental prostheses printed with 0° and 45° was nonsignificant, which contradicts the findings of the present study. This contradiction may be related to the differences in 3D-printed resin materials and the fact that Park et al's [25] study did not involve any kind of aging or cement.

Nold et al [3] investigated the effect of thermomechanical aging on the fracture strength of 3-unit fixed dental prostheses oriented either with a surface (occlusal, distal, and palatal) placed perpendicular to the build platform or with a 45° between the occlusal surface and the build platform (oblique). The authors [3] reported that only the difference between the 3-unit interim fixed dental prostheses printed with 45° and printed with their palatal surface perpendicular to the build platform showed difference before aging, with oblique placement resulting in higher values. However, none of the specimens placed with their occlusal or palatal surfaces perpendicular to the build platform survived the thermomechanical aging (250000 cycles, 98 N), whereas only 2 specimens of distally placed and 1 specimen of obliquely placed 3-unit interim fixed dental prostheses survived thermomechanical aging. All specimens survived the thermomechanical aging in the present study and this contradiction may be associated with the different cement used in Nold et al's [3] study as well as with the differences in the materials tested and parameters of thermomechanical aging. In another study on the effect of build direction and artificial aging (storage in distilled water at 37°C for

21 days) on the fracture strength of 3-unit interim fixed dental prostheses, specimens positioned with their distal surfaces facing the build platform showed higher values than those placed with their occlusal surfaces facing the platform, regardless of the materials tested (NextDent C&B, Freeprint temp, and 3Delta temp) [20]. However, positioning a fixed dental prosthesis with its distal surface perpendicular to the build platform increases the duration of the printing process because of the increased number of layers [20], even though the supports are placed away from the occlusal surface.

There are several studies on the comparison between additively and subtractively manufactured interim fixed dental prostheses [2-4, 20, 23]. Henderson et al [2] compared additively and subtractively manufactured interim fixed dental prostheses, and reported that milled 3-unit interim fixed dental prostheses endured higher loads regardless of storage time and loading rate. Similarly, Abad-Coronel et al [4] stated that milled interim fixed dental prostheses endured higher loads than 3D-printed 3-unit interim fixed dental prostheses after 5000 cycles of thermocycling. However, the printing orientation or the presence of any kind of cement was not disclosed [4]. Another study showed that milling and 3D printing with a 45° with the mesial side facing the build platform led to similar fracture strength values after thermomechanical aging when cemented on acrylic resin abutments with zinc-oxide based cement [3]. Reymus et al [20] compared different 3D-printed interim restorative materials (NextDent C&B, Freeprint temp, and 3Delta temp) with a milled PMMA (TelioCAD) on a steel abutment model without cementation. The authors [20] reported that milled PMMA showed lower fracture strength values compared with 2 of the 3D-printed materials (NextDent C&B and 3Delta temp) before distilled water storage, whereas the highest values were observed in milled PMMA 3-unit interim fixed dental prostheses after storage (37°C for 21 days). Fixed dental prostheses printed by using different methods (SLA, digital light processing (DLP), and fused deposit modelling (FDM)) have also been compared with milled

PMMA in a recent study [23]. Park et al [23] reported that SLA printed 3-unit fixed dental prostheses had higher flexural strength than milled PMMA. Nevertheless, a direct comparison between the present study and those previous studies [2-4, 20, 23] might be misleading considering the differences in tested materials, aging processes, and cements.

The masticatory forces in the molar region were reported to be around 350 N [26], while it may reach up to 900 N [27]. Considering that the most commonly encountered failure of interim restorations is fracture [24], it is critical for an interim restoration to withstand these loads, particularly when considered for a long-term rehabilitation. The printing orientations tested in the present study resulted in 3-unit interim fixed dental prostheses that may withstand physiological occlusal forces. However, 3-unit fixed dental prostheses printed with either 45° (907.2 N) or 90° (824.5 N) while using the 3D print resin tested may be susceptible to fracture for those patients with bruxism. Nevertheless, these results should be interpreted carefully as only one type of cement was used in the present study and the specimens were cemented on cobalt-chromium models, which have higher elastic modulus compared to dental hard tissues. Future in vivo studies are needed to corroborate the findings of the present study.

Failure types were evaluated under two categories as crack and restoration fracture, considering the results of the previous studies [4, 8, 28]. No failure was observed in any of the specimens during thermomechanical aging. However, catastrophic failures occurred in the connector, retainer, and pontic areas, where the stress was concentrated during static loading. The number of fractured specimens in milled group was nonsignificantly higher than those of cracked specimens, which may be attributed to the resiliency of the material tested. Considering that cracked restorations are more likely to be retained intraorally, milled 3-unit interim fixed partial dentures may result in additional appointments for remake. However, considering the limited number of studies on the fracture mechanics of 3D-printed interim fixed dental prostheses, future in vivo studies should corroborate this interpretation.

A limitation of the present study was that it was limited to 1 3D-printed and 1 milled CAD-CAM restorative material. Material type, 3D printing technologies, and other 3D printing parameters such as layer thickness and post polymerization processes may lead to different results. Recent studies [23, 24] have reported that polylactic acid, which is a nontoxic and environment-friendly polymer derived from renewable resources [24] might be used for the fabrication of interim restorations. However, effect of printing orientation on polylactic acid has not been investigated in those studies [23, 24]. In addition, thermomechanical aging was performed by using distilled water. However, using artificial saliva as the aging medium would approximate the test design more to the clinic [3]. No surface treatments such as polishing or glazing was performed as the present study aimed to focus on the intrinsic fracture strength of the materials tested. However, additional glazing or polishing may affect fracture strength and how a restoration is affected by aging processes. Finally, future studies investigating the effect of printing orientation on the accuracy and fit of 3D-printed interim fixed dental prostheses might elaborate the knowledge on additive manufacturing.

5. CONCLUSIONS

Within the limitations of the current study, following conclusions were drawn:

1. Printing orientation significantly affected the fracture strength of the 3D-printed interim resin tested.
2. For the tested 3D-printed resin, printing with 30° and 150° led to similar fracture strength with that of printing with manufacturer’s recommended orientation (occlusal

surface positioned to the build platform, 0°). However, only printing with 0° resulted in similar fracture strength with the milled PMMA tested.

Declaration of interest

The authors declare no conflict of interest. The authors do not have any financial interest in the companies whose materials are included in this article.

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Author statement

The authors of the manuscript contributed in the following ways to the submitted manuscript:

Almira Ada Diken Turksayar: Conceptualization, Writing - Review & Editing, Investigation

Mustafa Borga Donmez: Conceptualization, Writing - Original Draft, Writing - Review & Editing

Emin Orkun Olcay: Conceptualization, Methodology, Investigation

Münir Demirel: Resources, Methodology

Esra Demir: Investigation, Methodology

Declaration of interests

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

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TABLES

Table 1. Descriptive statistics of the fracture strength values

	Fracture Strength (N)	
Printing Orientation	Median (Min-Max)	Mean ±SD
Control (Milled)	1623.5[d] (1477.9-1779)	1623.4 ±111.5
0°	1094.8[cd] (988-1119.4)	1066.6 ±54
30°	969.5[bcd] (929.6-1096.7)	998.5 ±68.3
150°	954[bc] (912.5-1083.3)	971.6 ±55.3
45°	907.2[ab] (842.9-942.3)	909.2 ±27.8
90°	824.5[a] (805.5-913.4)	831.2 ±30.1

* Different superscript lowercase letters in same column indicate significant differences among groups (*P*<.05).

Table 2. Frequency of the failure types observed after load-to-failure test

	Failure Type	
Printing Orientation	Crack	Fracture (connector, retainer, and pontic)
Control (Milled)	3 (%30)	7 (%70)
150°	6 (%60)	4 (%40)
90°	5 (%50)	5 (%50)
45°	5 (%50)	5 (%50)
30°	6 (%60)	4 (%40)
0°	5 (%50)	5 (%50)

*Chi-square value:2.400, df: 5, *P*= .791, α =.05

FIGURES

Figure 1. Cobalt-chromium abutment model (A: Buccal aspect; B: Occlusal aspect; C: Proximal aspect; D: Cemented 3-unit interim fixed dental prosthesis)

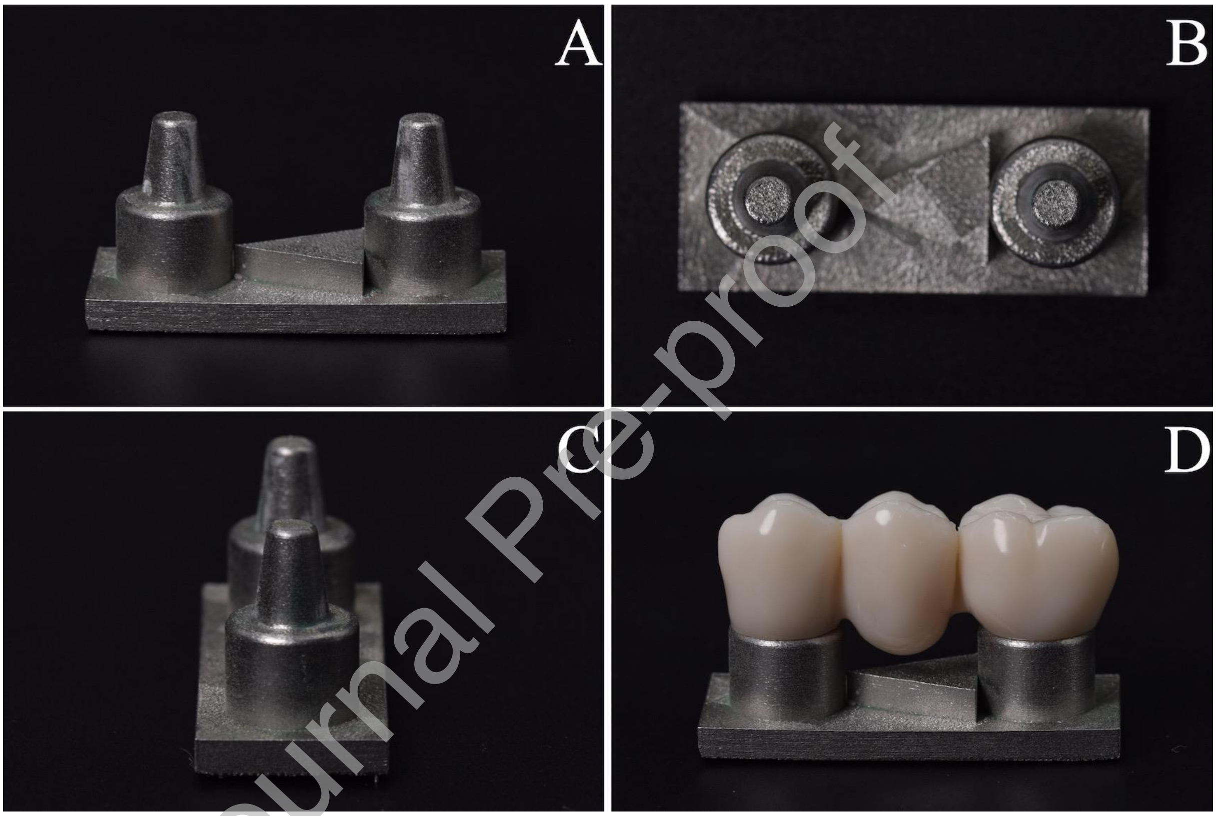

Figure 2. Additively manufactured 3-unit interim fixed dental prostheses with different build orientations

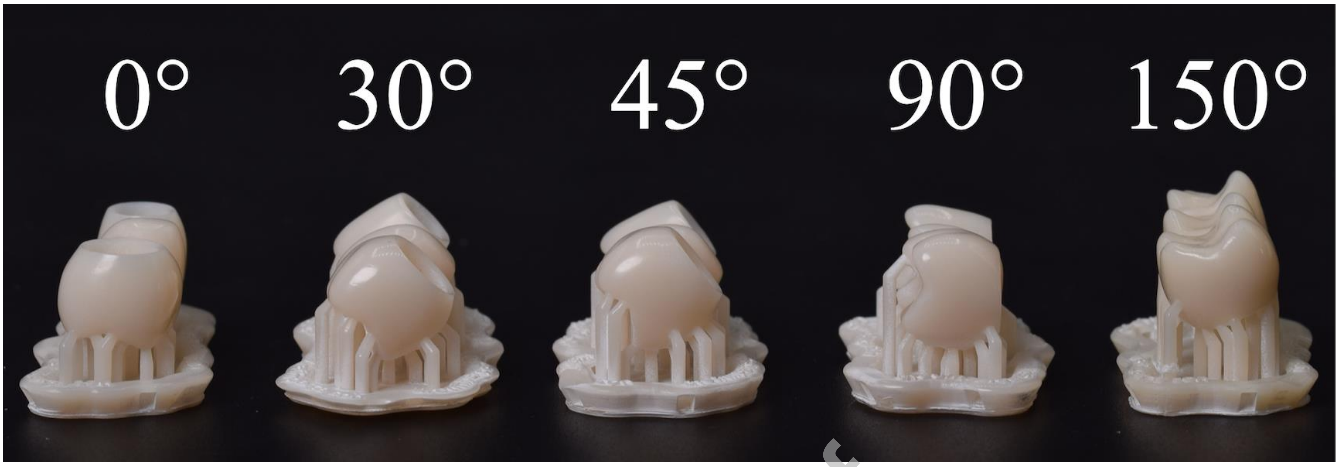

Figure 3. Bar graph of the median fracture strength values of test groups (Different superscript lowercase letters in same column indicate significant differences among groups (*P*<.05))

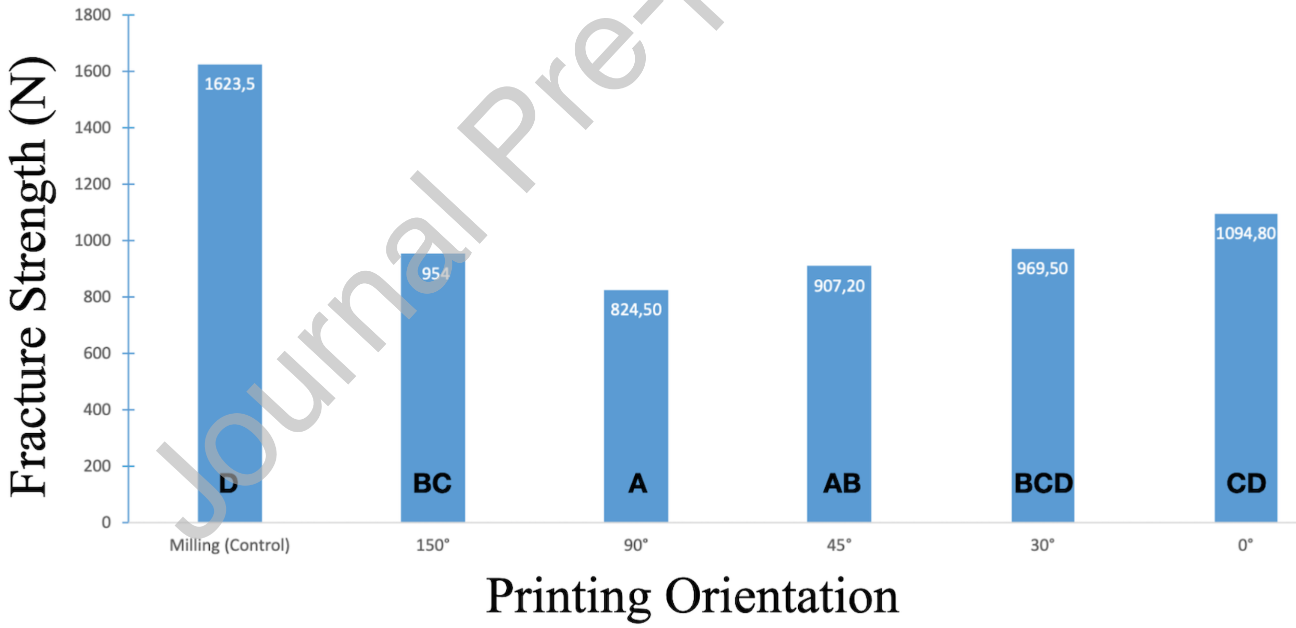

Figure 4. Different failure types observed (A: Pontic fracture; B: Retainer fracture; C: Crack; D: All failures in one model)