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ORIGINAL ARTICLE

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Effect of printing angle and aging of a 3D-printed resin for provisional prostheses: an in vitro study on fracture resistance

Efeito do ângulo de impressão e do envelhecimento de uma resina impressa em 3D para próteses provisórias: um estudo in vitro sobre resistência à fratura

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ABSTRACT

Objective: The objective of this study is to evaluate the effect of printing angulation and aging on the fracture resistance of 3D-printed resin for provisional prostheses: an in vitro study. **Material and Methods:** Specimens of 3D-printed resin with dimensions of 25×2×2 mm were processed according to the manufacturer's recommendations. Each experimental group consisted of n=5, categorized as follows: 0°, 45°, 90°, 0°A, 45°A, 90°A. Surface characterization was performed using scanning electron microscopy (SEM) (n=1). The specimens in groups 0°A, 45°A, and 90°A underwent aging in an incubator for 60 days at a temperature of 37 °C ± 0.5 °C in distilled water. All experimental groups were tested for three-point bending resistance using a universal testing machine, equipped with a 100 kgf load cell, set to a constant speed of 5 mm/min. Flexural strength values were recorded in megapascals (MPa). The mechanical strength data of the experimental groups were analyzed using a two-factor ANOVA test ($p < 0.05$) to assess the effects of printing angulation and aging. The findings from surface microscopy and fractography were qualitatively presented. **Results:** Distinct surface characteristics were identified in each experimental group, with the printed layers being more evident in the 45° and 90° angulations. A reduction in mean flexural strength values was observed for the 0° and 45° angulations after aging; however, no statistically significant differences were identified for the studied factors. The fractured specimens exhibited multiple fragments. **Conclusion:** Printing angulation and aging did not affect the mechanical performance of the 3D-printed resin for provisional prostheses.

KEYWORDS

Dental prosthesis; Digital technology; Flexural strength; Printing Angle; Three-dimensional printing.

RESUMO

Objetivo: O objetivo deste estudo é avaliar o efeito da angulação de impressão e do envelhecimento na resistência à fratura de resina impressa em 3D para próteses provisórias: um estudo in vitro. **Material e Métodos:** Amostras de resina impressa em 3D com dimensões de 25×2×2 mm foram processadas de acordo com as recomendações do fabricante. Cada grupo experimental consistiu de n=5, categorizados da seguinte forma: 0°, 45°, 90°, 0°A, 45°A, 90°A. A caracterização da superfície foi realizada por microscopia eletrônica de varredura (MEV) (n=1). As amostras dos grupos 0°A, 45°A e 90°A foram submetidas ao envelhecimento em incubadora por 60 dias a uma temperatura de 37 °C ± 0,5 °C em água destilada. Todos os grupos experimentais foram testados para resistência à flexão de três pontos usando uma máquina de teste universal, equipada com uma célula de carga de 100 kgf, ajustada para uma velocidade constante de 5 mm/min. Os valores de resistência à flexão foram registrados em megapascais (MPa). Os dados de resistência mecânica dos grupos experimentais foram analisados usando um teste ANOVA de dois fatores (p < 0,05) para avaliar os efeitos da angulação de impressão e envelhecimento. Os achados da microscopia de superfície e da fratografia foram apresentados qualitativamente. **Resultados:** Características de superfície distintas foram identificadas em cada grupo experimental, com as camadas impressas sendo mais evidentes nas angulações de 45° e 90°. Uma redução nos valores médios de resistência à flexão foi observada para as angulações de 0° e 45° após o envelhecimento; no entanto, nenhuma diferença estatisticamente significativa foi identificada para os fatores estudados. Os espécimes fraturados exibiram múltiplos fragmentos. **Conclusão:** A angulação de impressão e o envelhecimento não afetaram o desempenho mecânico da resina impressa em 3D para próteses provisórias.

PALAVRAS-CHAVE

Ângulo de Impressão; Impressão tridimensional; Prótese Dentária; Resistência à Flexão; Tecnologia Digital.

INTRODUCTION

Additive manufacturing (AM), particularly three-dimensional (3D) printing, has garnered significant attention in dentistry due to its versatility, precision, and potential for streamlining the fabrication of dental restorations. Technologies such as Digital Light Processing (DLP) and Stereolithography (SLA) have made it feasible to produce temporary crowns and fixed partial dentures with greater customization and reduced production time. However, as these materials are introduced into clinical workflows, it becomes essential to understand their physical and mechanical behavior to ensure safe and effective use.

The selection of materials for 3D-printed provisional restorations requires not only biocompatibility but also sufficient mechanical strength to withstand occlusal forces and thermal variations present in the oral environment. Evaluating the mechanical performance of these materials helps validate manufacturers' claims and allows comparisons with conventional materials. This aids clinicians in choosing the most appropriate material for clinical longevity [1].

Numerous studies have been proposed to investigate the mechanical performance, surface properties, color stability, water absorption, and aging of 3D-printed resins as materials for temporary crowns or fixed bridges [1-10]. The findings from Park et al.'s research [8] suggest that 3D-printed products fabricated with Digital Light Processing (DLP) and Stereolithography (SLA) technologies can be used in clinical practice. Resins for 3D-printed provisional crowns and bridges using a low-cost stereolithography 3D printer exhibit adequate mechanical properties for intraoral use, as the elastic modulus and maximum stress of the 3D-printed samples are comparable to or greater than those of conventional resin samples [11]. Pereira et al. [9] emphasizes the dimensional accuracy of 3D-printed provisional crowns, which is essential for the stability of temporary restorations and for evaluating fracture resistance under different angulations. The literature on the mechanical behavior of 3D-printed materials for dentistry is scarce, making further in vitro and in vivo research essential [10].

Further investigation is needed to compare the mechanical properties and biocompatibility of 3D-printed resins to implement them in routine clinical practice [1]. However, to date, there is a lack of evidence regarding the effect of printing layer thickness and post-printing processes on the mechanical properties of 3D-printed temporary restorations [1]. Additionally, the effect of printing orientation and aging on the mechanical properties of these resins remains unclear [12,13].

Based on the above, the objective of this study was to evaluate the effect of printing angle and aging of a 3D-printed resin for provisional prostheses through an in vitro study on flexural strength.

The hypotheses tested were as follows:

- Null Hypothesis (H0): Printing angle and aging do not significantly affect the fracture resistance of the 3D-printed resin;
- Alternative Hypothesis (H1): Printing angle and/or aging significantly affect the fracture resistance of the 3D-printed resin.

MATERIAL AND METHODS

Fabrication of specimens

Two types of specimens were fabricated using 3D-printed resin (PriZma 3D Bio Prov Resin, Makertech Labs, São Paulo, São Paulo, Brazil - composition: Proprietary Acrylated and Triacrylated Monomers, Amorphous Silica, Fillers, Meta-Acrylated Oligomers, Diphenyl

(2,4,6-trimethylbenzoyl)), at different printing angles, as described by Alshamrani et al. [1]. Bar-shaped specimens (25 × 2 × 2 mm), following ISO 4049 standards [14], were used for mechanical flexural strength testing. Block-shaped specimens (25 × 12 × 2 mm) were fabricated for surface characterization via microscopy.

The 3D models were created using 3D Builder software (Microsoft, USA), which served as the CAD modeling tool. The models were exported in STL (Standard Tessellation Language) format and imported into the slicing software provided with the Anycubic Photon S Talmax Dental Prosthesis 3D Printer (Curitiba, Paraná, Brazil), which was used to define the printing parameters and execute the slicing process. The specimens were printed at 0°, 45°, and 90° orientations relative to the build platform, with a layer thickness of 50 μm (Figure 1) (Table I).

After printing, the specimens were cleaned in isopropyl alcohol using an ultrasonic bath and post-cured in a UV chamber, following the manufacturer's instructions.

After completing the polymerization process, the dimensions of the specimens were verified using a caliper [7]. Subsequently, the fabricated specimens were stored in distilled water in an oven (FANEM, Orion Culture Oven 502) at a temperature of 37°C. After 24 hours of storage, the analyses were initiated.

Experimental groups and sample size

The sample size was calculated using Minitab (version 16.1 for Windows, Pennsylvania, USA) based on the standard deviation data reported in a similar study by Alshamrani et al. [1]. This calculation ensured that n = 5 per group would provide a statistical power of 80.0% for the flexural strength analysis.

Six experimental groups were formed according to the printing orientation (0°, 45°, 90°) and the presence or absence of aging (n=5). The aging process followed the methodology described by Alshamrani et al. [1], in which specimens were stored for 60 days in distilled water at 37 °C ± 0.5 °C in a laboratory oven. This protocol is supported by literature as a simulation

Table I - 3D printing parameters used in specimen fabrication

Parameter	Value
Printer model	Anycubic Photon S Talmax
Layer thickness	50 µm
Printing angles	0°, 45°, 90°
Resin used	PriZma 3D Bio Prov
CAD software	3D Builder
Slicing software	Anycubic Photon Workshop (default)
Post-processing	Ultrasonic cleaning + UV curing
Curing temperature/time	Manufacturer's protocol

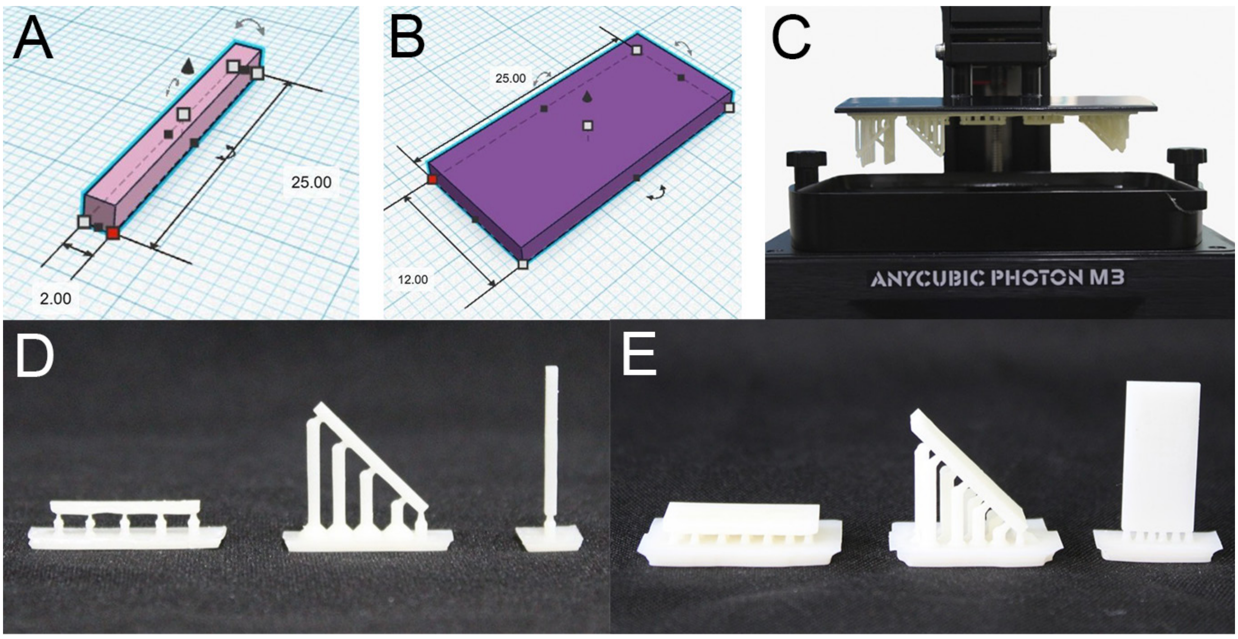

Figure 1 - (A) and (B) CAD design of the specimens; (C) Printing of the specimens; (D) Bar specimens with 0°, 45°, and 90° angles; (E) Block specimens with 0°, 45°, and 90° angles. Source: Authors.

of prolonged intraoral conditions, enabling the assessment of hydrolytic degradation and the potential effects on the mechanical properties of polymer-based restorative materials. Additionally, all mechanical specimens were fabricated according to ISO 4049 standards [14], which define the required dimensions and procedures for polymer-based restorative materials.

Surface characterization

Representative specimens from each experimental group (N=1) were evaluated for surface characteristics using a Stereo Microscope (Discovery V20, Zeiss, Göttingen, Germany) and a Scanning Electron Microscope (SEM) (HITACHI, Model TM300), with the aim of identifying changes and the presence of pores.

Aging

The specimens were subjected to aging in an oven (FANEM, Orion Culture Oven 502) for 60 days at a temperature of 37 °C ± 0.5 °C in distilled water.

Mechanical strength

The three-point flexural strength test was performed using a universal testing machine, EMIC model DL-1000 (EMIC DL 1000, São José dos Pinhais, Brazil). The specimens were fixed between two supports, with a span distance of 20 mm, and subjected to stress until fracture [1]. The test was conducted before and after aging.

The machine was programmed with a 100Kgf load cell at a constant speed of 5 mm/min. Flexural strength values were obtained in megapascals (MPa) using Formula 1 [14]. Where γ is the flexural strength, F is the load at the fracture point, D is the support span length, b is the width of the sample, and d is the thickness of the sample.

$$\gamma = 3FD / 2bd2$$

Fracture analysis

The fractured specimens were analyzed using a stereo microscope (Discovery V20, Carl Zeiss, Germany) and a Scanning Electron Microscope (SEM) (HITACHI, Model TM300) to determine the fracture characteristics.

Results analysis

The results were tabulated and analyzed using Minitab (version 16.1 for Windows, Pennsylvania, USA), with a significance level set at 5%. The mechanical strength data of the experimental groups were subjected to the Kolmogorov-Smirnov test to determine data normality. After confirming the normality of the results, the two-factor ANOVA statistical test ($p < 0.05$) was applied to evaluate the effect of the factors printing angle and aging. The findings from surface microscopy and fractography were presented qualitatively.

RESULTS

Surface analysis

Scanning electron microscopy (SEM) revealed distinct surface features among the experimental groups. At 200× and 1,000× magnifications, the 0° specimens exhibited a smoother surface morphology with minimal interlayer markings, indicating a more uniform curing pattern. In contrast, the 45° and 90° specimens displayed more pronounced layer lines, with the 90° group showing the most irregular surface, characterized by visible step-like structures and voids between the printed layers (Figure 2). These features suggest a correlation between printing orientation and the topographic quality of the resin surface.

Mechanical performance

Flexural strength values varied across printing orientations and aging conditions. After aging, a reduction in mean flexural strength was observed in the 0° and 45° groups. The 90° group, however, showed a slight increase in average strength post-aging. Despite these trends, two-way ANOVA results indicated that neither printing orientation nor aging, nor the interaction between both factors, significantly influenced fracture resistance ($p > 0.05$) (Tables II and III).

Fracture analysis

The fractured specimens exhibited a variable number of fragments, depending on the printing angle and aging condition. In non-aged groups, specimens fractured into 2 to 3 fragments for 0° and 90°, and 2 to 5 fragments for 45°. In aged groups, fragmentation ranged from 2 to 3 for 0°,

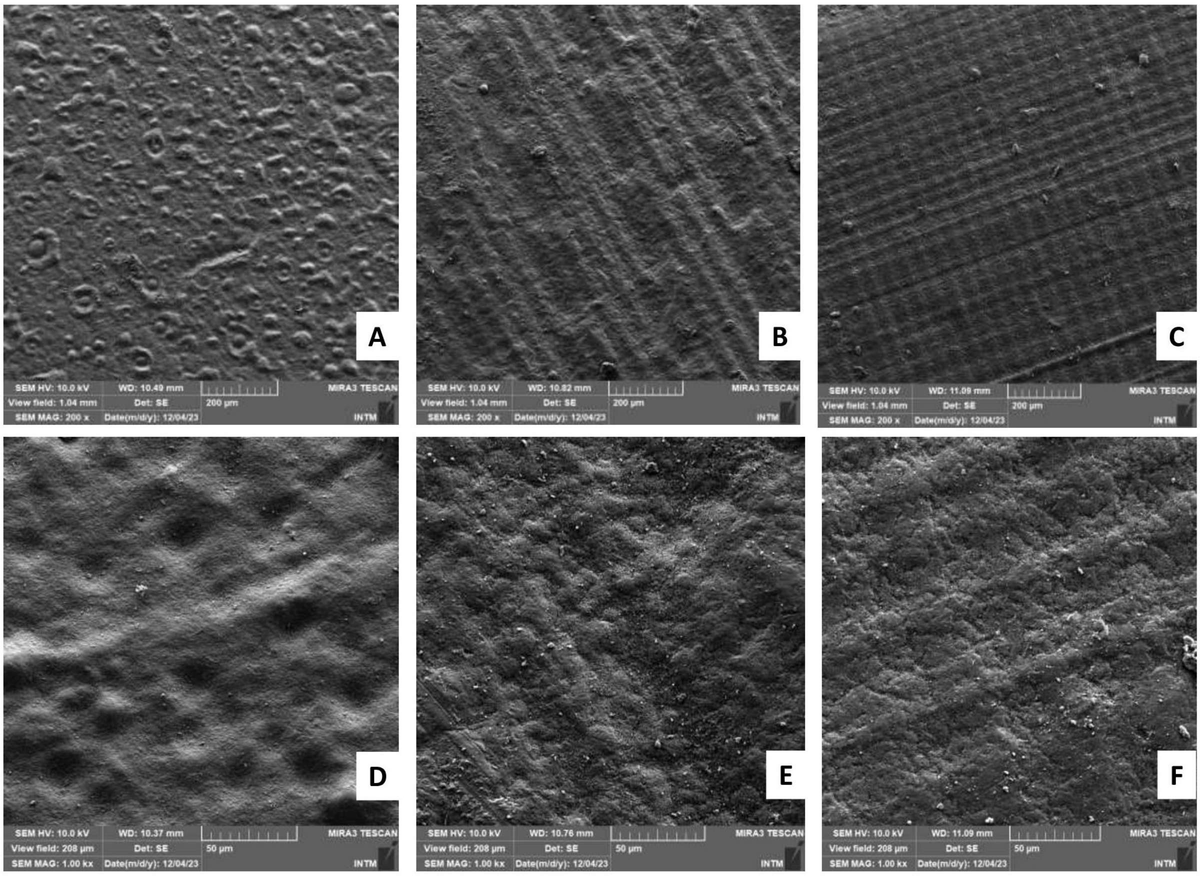

Figure 2 - SEM images of specimen surfaces at 200× magnification: (A) 0°; (B) 45°; (C) 90°; and at 1,000× magnification: (D) 0°; (E) 45°; (F) 90°. Note: Layered structures and surface porosities are more visible at higher angles. Source: Authors.

Table II - Flexural strength values before and after aging (MPa)

Experimental Groups (n=5)		Mean	Standard Deviation	Minimum	Median	Maximum
Printing Orientation	Aging					
0°	No	215.31	20.54	180.28	222.94	233.44
45°	No	215.27	12.09	203.25	209.63	233.72
90°	No	197.55	21.10	162.84	202.41	219.19
0°	Yes	187.4	62.5	114.1	231.4	235.3
45°	Yes	184.0	37.4	118.5	194.3	212.8
90°	Yes	208.61	15.67	191.91	204.38	231.66

Table III - Analysis of variance between the factors printing orientation and aging

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Printing Orientation	2	60.2	30.08	0.03	0.973
Aging	1	193.0	193.02	1.76	0.197
Printing Orientation *Aging	2	2771.1	138.57	1.26	0.300
Error	24	26290,8	109.45		

DF = degrees of freedom; Adj SS = adjusted sum of squares; Adj MS = adjusted mean square.

2 to 4 for 45°, and consistently 2 fragments for 90°, although some of these lost portions after fracture (Figure 3). SEM analysis of internal fracture surfaces also revealed common features such

as crack initiation zones, hackle marks (fine lines radiating from the origin of fracture), twisted hackles, and resin pull-out areas (Figure 4). These features suggest interlayer weaknesses and differences in fracture behavior depending on orientation.

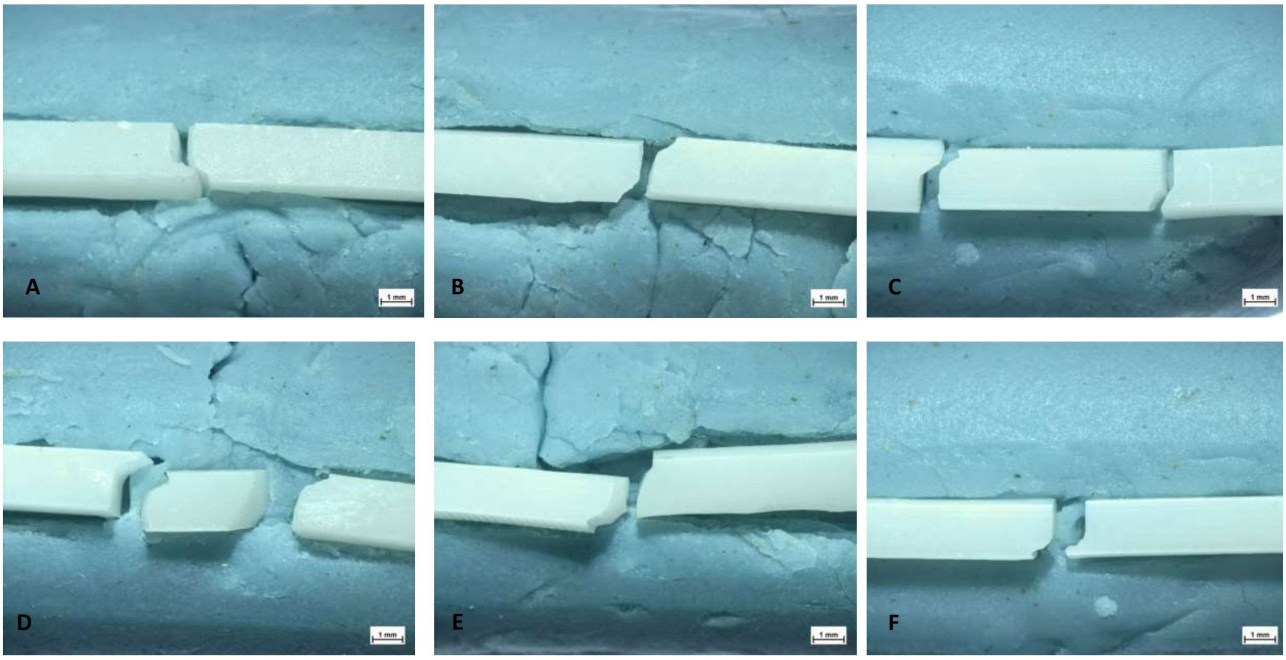

Figure 3 - (A) Group 0° without aging, specimen 4 with two fragments; (B) Group 45° without aging, specimen 4 with two fragments; (C) Group 90° without aging, specimen 1 with three fragments; (D) Group 0° with aging, specimen 2 with three fragments; (E) Group 45° with aging, specimen 2 with two fragments; (F) Group 90° with aging, specimen 2 with two fragments. Source: Authors.

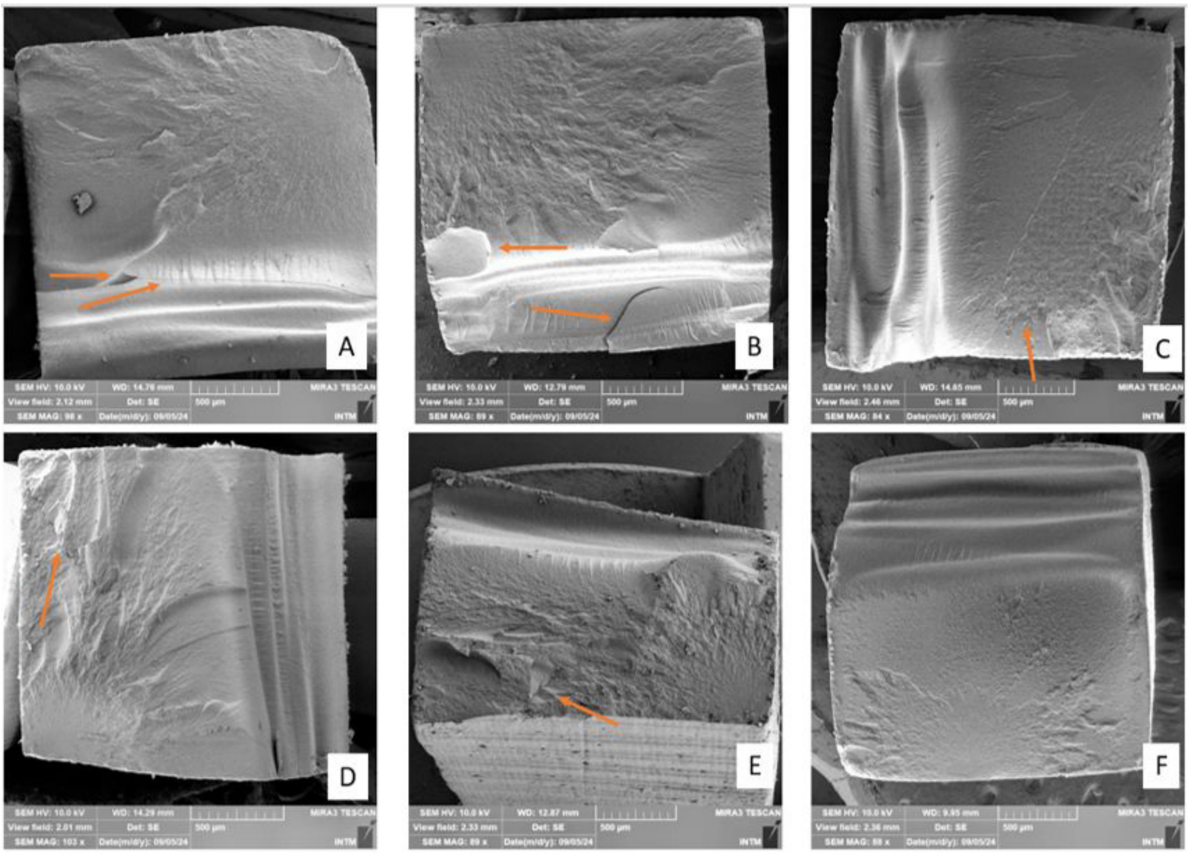

Figure 4 - SEM fractographic images of internal fracture surfaces. (A) Group 0° without aging, specimen 4; (B) Group 45° without aging, specimen 4; (C) Group 90° without aging, specimen 1; (D) Group 0° with aging, specimen 2; (E) Group 45° with aging, specimen 2; (F) Group 90° with aging, specimen 2. Arrows indicate internal cracks, twisted hackles, resin pull-out, and printed layers. Source: Authors.

DISCUSSION

Based on the results obtained in this research, the Null Hypothesis (H0) was accepted, indicating that printing angulation and aging did not produce statistically significant differences in the fracture resistance of 3D-printed resin for provisional prostheses.

The literature describes how surface morphology can vary with printing orientation. According to Aljehani et al. [13], additive manufacturing often results in a layered or wavy surface, especially at steeper angles. The 0° group tends to present a smoother surface, while the 90° group is typically characterized by rough, stepped edges and voids, and the 45° group by a weave-like pattern. These patterns, while observed in our SEM images, were presented earlier in the results section to ensure proper structure of the manuscript.

Regarding the effect of printing angle, several studies—Aljehani et al. [13], Alageel et al. [12], Turksayar et al. [5], Kleßer et al. [6], Derban et al. [4], Reymus et al. [10], and Tahayeri et al. [11]—reported statistically significant differences in mechanical properties. However, these findings do not align with our results. Differences may stem from variations in printing systems, material compositions, and methodologies. For example, Alageel et al. [12] highlighted that factors such as chemical formulation, molecular structure, and filler content significantly affect resin performance. Moreover, different studies evaluated distinct specimen types, such as crowns or bridges, and employed diverse orientations, printing parameters, and aging protocols.

Regarding aging, our findings partially align with Alageel et al. [12], who found that brushing simulation and thermocycling did not affect the fracture resistance of certain resins, although other materials like NextDent did exhibit aging effects. The similarity in printing orientation and resin composition may explain this consistency. On the other hand, contrary results were reported by Alshamrani et al. [1], Kleßer et al. [6], Myagmar et al. [7], Berli et al. [2], and Reymus et al. [10], where aging—either through thermocycling or prolonged water storage—significantly affected mechanical performance. These discrepancies emphasize the need for standardized protocols and further comparative studies.

The fracture behavior in our study showed a higher number of fragments in 45°-printed specimens, regardless of aging. Alshamrani et al. [1] noted that when printed layers are aligned parallel to the loading direction, delamination is more likely due to tensile stress. Our SEM images showed typical fractographic features such as voids, crack initiation zones, hackle marks, and twisted hackles—findings supported by Derban et al. [4] and Kleßer et al. [6]. These voids, often found between layers, can act as internal defects and compromise mechanical integrity.

The weakest zones in DLP-printed specimens are typically the interlayer regions, prone to failure under shear stress [6]. Additionally, the surface roughness observed under SEM at 200X magnification may influence crack propagation. As discussed by Pereira et al. [9], SLA systems tend to produce smoother surfaces compared to DLP systems due to the nature of their layer-by-layer curing mechanisms. Surface morphology and layer adhesion directly influence the mechanical strength, as reinforced by Reymus et al. [10].

A limitation of this study is the relatively short aging period (60 days). Longer durations may provide more clinically relevant data. Additionally, testing only one resin type limits the generalizability of our findings. Future research should explore different aging protocols (thermal and mechanical), use anatomical specimens, and evaluate additional printing parameters to better understand their impact on mechanical behavior.

CONCLUSION

Based on the results obtained, printing angulation and aging were not factors that affected the fracture resistance of a 3D-printed resin for the fabrication of provisional prostheses.

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Author's Contributions

GMLS: Methodology, Software, Writing – Original Draft Preparation, Formal Analysis, Investigation, Visualization. SMAS: Formal Analysis, Writing – Review & Editing. MTLMB: Formal Analysis, Writing – Review & Editing. AOSA: Formal

Analysis, Writing – Review & Editing. AJTN: Formal Analysis, Investigation, Writing – Review & Editing, Visualization. LALB: Formal Analysis, Investigation, Writing – Review & Editing, Visualization. OJRLN: Conceptualization, Methodology, Validation, Supervision, Project Administration. VMGF: Conceptualization, Methodology, Validation, Supervision, Project Administration.

Conflict of Interest

There is no conflict of interest among the authors of this research.

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Regulatory Statement

Not applicable.

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