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ORIGINAL ARTICLE

Effect of the Printing Angle on Flexural Strength, Microhardness, and Surface Roughness of Three-Dimensionally Printed Resin for Provisional Restorations

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ABSTRACT
Objective: To evaluate the influence of three angles (0°, 45°, and 90°) on the mechanical properties and surface characteristics of the specimens produced by a 3D printer and resin for provisional restorations. **Material and Methods:** In this *in vitro* study, ten bars (4 × 2 × 10 mm) were produced for each experimental group (n = 10), designed in the Meshmixer software and printed on a 3D printer. The bars were tested immediately, without aging. They were subjected to a three-point bending test in a universal testing machine, and the surface roughness was measured by a contact profilometer. Microhardness was measured by a microhardness tester and the surface roughness of the specimens was evaluated with a scanning electron microscope. **Results:** The flexural strength of the 0° group (236.20 ± 29.73) was significantly higher than those of the 45° (155.80 ± 36.19) and 90° (138.70 ± 48.20) groups. Similarly, the surface roughness of the 0° group (0.10 ± 0.06) was significantly lower than the 45° (1.62 ± 0.55) and 90° (0.97 ± 0.22) groups. Microhardness was similar among the groups. **Conclusion:** The 0° angulation, with deposition of the layers on the printed object so that they are oriented perpendicular to the direction of application of forces, resulted in the best resistance to bending and lower roughness, which may contribute to better clinical behavior.

Keywords: Printing, Three-Dimensional; Flexural Strength; Stereolithography.

Introduction

The use of additive manufacturing techniques or three-dimensional (3D) printing is being applied more frequently every day in the field of dental rehabilitation for the production of temporary restorations, bases for complete dentures, maxillofacial prosthetics, orthodontic aligners, surgical guides, and dental implants [1,2]. Among the various additive manufacturing technologies, the three most used in dentistry are related to the use of photoactivation: laser stereolithography (SLA), injection of a photopolymer, and light activation (digital light production [DLP]) [3].

The number of resins for temporary restoration printing available on the market is increasing rapidly. In general, they can be classified according to their chemical composition into two types: acrylic or monomethacrylate-based resins and bisacrylic or dimethacrylate-based resins [4]. In addition to the technology used and the resin characteristics, various parameters influence the final results achieved by additive manufacturing, among which the thickness of the layer and the printing angle stand out [5].

Temporary crowns are of the utmost importance in tissue conditioning, reestablishment of occlusion, mastication functions, and aesthetics in implant-supported rehabilitations. The use of conventional techniques to obtain temporary restorations, based on acrylic or bis-acrylic resins, produces good biocompatibility, aesthetics, and stability in the oral environment. However, these good results are dependent on the ability of the dentist, assistant, or prosthodontist [6,7]. Digital techniques for obtaining these restorations can contribute to reducing errors, leading to a reduction in treatment time and material savings due to the accuracy of the results [8].

Features such as good marginal adaptation and low surface roughness favor the tissue response around temporary restorations. A prosthesis with high roughness and surface energy is potentially more vulnerable to plaque accumulation and more susceptible to the damaging consequences of this accumulation [9,10]. It is known that the adherence of microorganisms on the surface of restorations on implants is a factor that can be controlled but not eliminated. Thus, the accuracy of the adaptation, reduction of the gap, and gingival conditioning of single implant-supported prostheses are factors that should be paramount in the choice of new restoration acquisition techniques [11,12].

In the present study, we evaluated the material properties, flexural strength, roughness, and microhardness of different resin surfaces for temporary restorations obtained by additive manufacturing and by varying the printing angle. Our null hypothesis is that the printing angle does not influence the mechanical properties and surface characteristics of the 3D-printing resin.

Material and Methods

Independent Variable and Experimental Groups

The independent variable, printing angle, was tested at three different levels: 0°, 45°, and 90° relative to the printing base.

Specimens in the form of bars, with dimensions of 4 × 2 × 10 mm, were produced by additive manufacturing as described previously [13], using DLP technology with a layer thickness of 0.05 mm and three printing orientations (0°, 45°, and 90° inclination) [5]. Ten bars were produced for each of the experimental groups; they were not subjected to an aging period prior to mechanical tests. The specimens were designed in the Meshmixer software (Autodesk Inc., San Francisco, CA, USA) (Figure 1) and then prepared for 3D printing using the CHITUBOX software (CBD-Tech, Shenzhen, China). All specimens were produced using the same printer (Mikra Resin 3D Printer, Zhangzhou Echo Technology Co. Ltd., Zhangzhou, China) with liquid crystal display (LCD)/masked stereolithography (MSLA) printing technology and with a layer thickness of 0.05 mm and the same temporary restoration resin for 3D printing (AA Temp, PrintaX, Odonto Mega import, Ribeirão Preto, SP, Brazil). A base was designed for printing, which was printed in 12 layers, with a light exposure time of 70 seconds between each layer. For the bars, the light exposure time between the layers was 14 seconds. Once the printing was completed, the specimens along with the bases were removed from the printing tray and washed with isopropyl alcohol for 5 minutes in a tank placed on a vibrator that vibrated at a frequency of 50/60 Hz and a power of 40 W (Vibramaxx, Essence Dental, Brazil). Subsequently, the specimens were subjected to the post-curing process recommended by the manufacturer, with two cycles of 1 minute each in a curing chamber (Mikra Cure, Zhangzhou Echo Technology Co., Ltd., Zhangzhou, China), with exposure to LED UV light at 405 nm and 100 W of power. The bars were carefully removed from the printing bases with a diamond disc and separated according to the printing orientation.

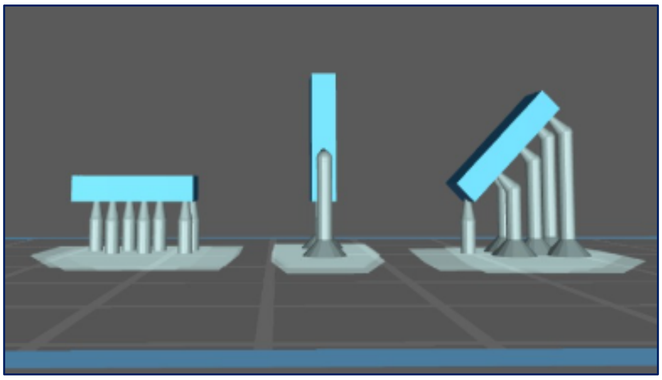

Figure 1. Original image from the software used (Meshmixer, Autodesk Inc, USA) illustrating the printing angles of the test specimens that were printed.

Flexure Strength Tests

For flexure strength test, ten specimens were used for each group. The three-point flexural strength test was performed using a universal testing machine (EMiC, Instron Brasil Equipamentos Científicos Ltda., São José dos Pinhais, PR, Brazil), with a speed of 0.5 mm per minute and a load cell of 500 N. The upper support point was made using the three-point bending device (Odeme Dental Research, Luzerna, SC, Brazil) at the center of the bar-shaped test specimen.

Hardness Evaluation

For hardness evaluation, one specimen was used for each group. Vickers microhardness was evaluated using a microhardness tester (HMV-G series, Shimadzu Corp., Kyoto, Japan), by making five micro-indentations in five different regions of each specimen. A load of 490.3 mN was applied for 15 seconds according to the ASTM E384 (2010) technical standard. The value was determined as the average of the five measurements and is expressed in HV.

Surface and Roughness Evaluation

For surface roughness evaluation, five specimens were used for each group. A 4 mm^2 area located at the center of each specimen served as the reading area for the test. A contact profilometer (Rugosimeter model TR210, Time Group Inc., Beijing, China) was used, with one reading performed for each of the specimens. The arithmetic roughness parameter (Ra) was calculated as the average/median of these five measures [13].

Scanning Electron Microscopy

Three randomly selected fragments from all experimental groups were gold sputtered and attached to stubs for qualitative evaluation of the surface by using a scanning electron microscope (model IT300, JEOL Ltd., Tokyo, Japan) at magnifications of 100×, 500×, and 1000×. The following parameters were used to obtain images in high vacuum: voltage of 20 kV; sample distance, 9.8 mm; lens aperture, 50.0.

Statistical Analysis

The Kolmogorov-Smirnov and Shapiro-Wilk tests were used to determine whether the data had a normal distribution. The data were normally distributed, so they are presented as the mean and standard deviation. For initial comparison of the effect of print orientation, the means of the three groups were compared with one-way analysis of variance (ANOVA) test followed by Tukey's test. GraphPad Prism version 5.0 (GraphPad Software, USA) was used for statistical analysis.

Results

The average and standard deviation results for flexural strength, Vickers hardness, and surface roughness of the three printing angles (0°, 45°, and 90°) are shown in Table 1. After the bending tests, there were no significant differences between the 45° and 90° groups. However, the 0° group showed significantly higher flexural strength than the 45° and 90° groups (Table 1). Each group showed similar Vickers hardness (Table 1). However, surface roughness differed significantly among the groups. The 45° group had the highest roughness, followed by the 90° group. The 0° group had the lowest surface roughness (Table 1).

Table 1. Mean (standard deviation) results for groups 1, 2, and 3.

Variables	G1 (0°)	G2 (45°)	G3 (90°)
Flexural strength (N/mm²)	236.20 (29.73) [a]	155.80 (36.19) [b]	138.70 (48.20) [b]
Vickers Hardness (hv)	20.30 (4.01) [a]	21.80 (2.25) [a]	21.00 (3.92) [a]
Roughness (ra)	0.10 (0.06) [a]	1.62 (0.55) [b]	0.97 (0.22) [c]

Flexural strength (N/mm²), Vickers hardness (hv), and roughness (Ra) of groups 1, 2, and 3. Values with the same letters are not significantly different (one-way analysis of variance followed by Tukey's test, p>0.05).

Scanning Electron Micrography

The images in column A of Figure 2 (100× magnification) show intact test specimens that did not undergo testing. It is possible to observe the direction of the programmed print for each angle in which the bars were printed. The lines are more parallel to each other and represent the form of the structure. Column B shows images at 1000× magnification after the bending test in the fractured region of the 3D-printed resin. There are two morphological patterns. In pattern 1, the lines are almost parallel to each other. These lines are the result of the compressive stress applied to the printed material, specifically the area where there was contact between the surface and the upper tip of the device used for the bending test. This local compression may have caused discrete crushing of each printed layer, resulting in the lack of parallelism of the lines. Pattern 2 indicates cleavage of the material, possibly caused by the tensile stress that developed in this area.

The images in Figure 3 show the surface of the bars used in the tests at 33× magnification. The surfaces differ according to the angle at which they were printed, with A (0°) showing a lower roughness than B (90°) and C (45°). These images confirm the findings of the roughness test.

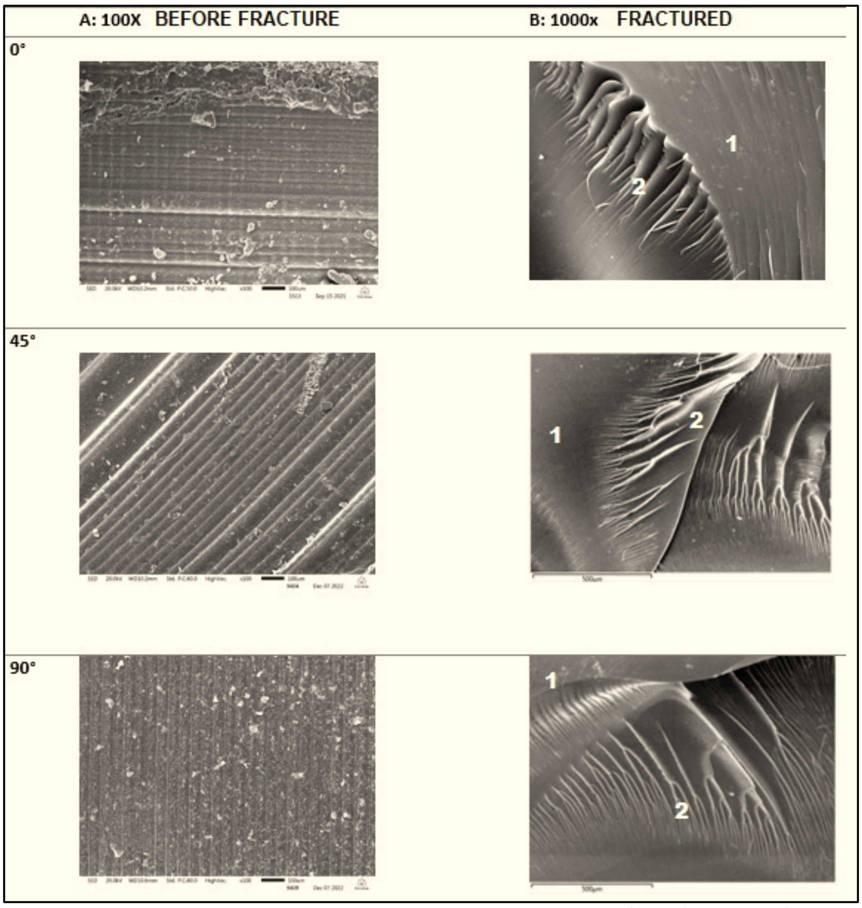

Figure 2. Images of three bars obtained with a printing angle of 0°, 45°, and 90°. Column A shows whole specimens at 100× magnification, before the bending test. Column B shows specimens at 1000× magnification after the bending test. The numbers 1 and 2 indicate two fracture patterns.

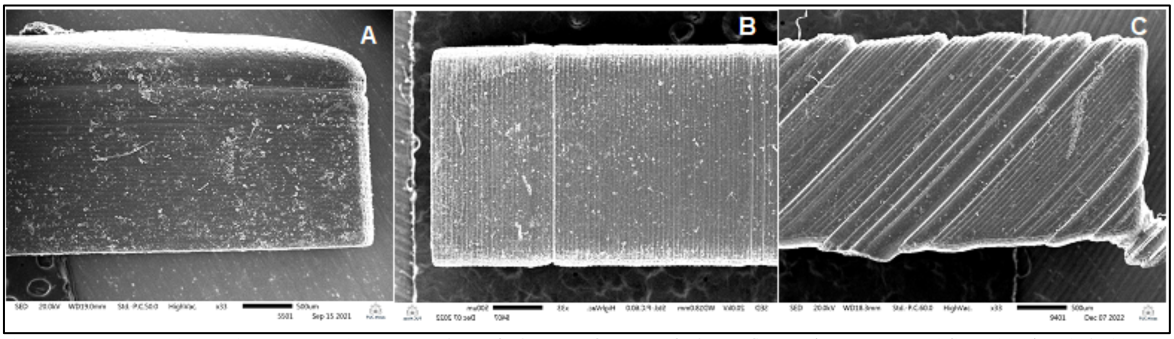

Figure 3. Scanning electron micrographs of the surfaces of three bars (33× magnification) with layers printed at (A) 0°, (B) 90°, and (C) 45° relative to the base.

Discussion

Reducing time and cost, increasing reliability and accuracy, and providing the ability to easily make objects with complex geometry are important considerations for adopting 3D-printing technologies. In addition, in this prototyping process, it is possible to reduce waste and to produce multiple objects at the same time while maintaining print accuracy even in complex geometries. Additive manufacturing techniques have been proposed as an alternative to subtractive manufacturing techniques and are used in various sectors in industry and health. With the development of digital technologies, professionals can reduce the time and space in terms of print processing and reduce material distortion [14-16].

In this *in vitro* study, we evaluated the effect of the printing angle by comparing the flexural strength, roughness, and microhardness of each bar-shaped test specimen.

The bars printed with layers at an angle of 0° relative to the platform showed higher flexural strength (236.20 ± 29.73) compared with the bars constructed with an angle of 45° (155.80 ± 36.19) or 90° (138.70 ± 48.20) (Table 1). Thus, for flexural strength, we rejected our null hypothesis. The 0° printing angle, which provides for the deposition of layers that will be oriented perpendicular to the direction of load application, increased the flexural resistance of the printed object. This same behavior has been observed in other studies [5,17,18]. The chemical interactions present in the same layer seem to provide better mechanical results than those between layers [17,18]. Moreover, the deformation pattern of the test specimens before their fracture was different according to the orientation of the layers relative to the application of the tension, suggesting that the stress between the layers caused by the application of the tension promotes "slipping" between the layers [17,18].

In another study, the authors reported results similar to our study: The prostheses printed at a 0° printing angle had the highest fracture resistance, resembling even the resistance of the milled temporary prostheses [19]. On the other hand, some authors have observed greater resistance to bending in the test specimens with the layers parallel to the direction of load application [20,21]. It should be noted that Unkovskiy et al. [20] reported in their discussion that before they performed the bending resistance test, they expected the highest resistance to be from the test specimens in which the layers would be oriented perpendicular to the direction of load application. The results presented by Park et al. [22] are different from those reported in the literature, as the specimens printed at 0° and 90° showed similar resistance to bending, demonstrating that parallel or perpendicular orientations to the direction of load application did not significantly interfere with bending resistance.

Regarding roughness, the specimens produced at a printing angle of 0° presented lower Ra values (0.10 ± 0.06), followed by those produced at 90° (0.97 ± 0.22) and 45° (1.62 ± 0.55) (Table 1). Thus, for surface roughness, we rejected our null hypothesis. These results are similar to a previous study [5]. In addition to evaluating roughness, these authors demonstrated that *Candida albicans* colonization was higher on the surfaces printed at 45°. There are other studies that have affirmed the importance of obtaining lower roughness to minimize plaque bacterial aggregation [23,24]. Mickeviciute et al. [24] also stated that reducing the roughness of the surface of a temporary restoration can favor color stability. Considering that the adaptation accuracy of 3D-printed restorations has been considered to be adequate [25,26], in a clinical approach, using additive manufacturing technology to manufacture temporary restorations tends to be an appropriate approach. Specimens obtained by additive manufacturing using the SLA technology showed lower surface roughness values, similar to those obtained through Bis-acrylic resin [13]. The limited literature reinforces the need for efforts to obtain more research on the roughness of 3D-printed resin prostheses currently used on the market, given the number of applications of use in dentistry and the potential influence of plaque bacterial-aggregating factors on the quality of the rehabilitation described earlier.

Regarding Vickers hardness, the specimens produced at a printing angle of 0° presented Hv values (20.30 ± 4.01) similar to those produced at 45° (21.80 ± 2.25) and 90° (21.00 ± 3.92) (Table 1). Thus, all the groups presented similar microhardness, confirming our null hypothesis. This may have occurred due to the polymerization process of the groups being the same. Each experimental condition received the same amount of energy to initiate and propagate the polymerization process. Additionally, it's important to note that the light application occurs in printing layers, and this was not influenced by printing orientation. Furthermore, at the end of the printing, during post polymerization process, there is a new light application for the polymerization of possible residual monomers, preventing any issues with polymer chains being too short or not having the appropriate degree of cross-linking between them. Consequently, the microhardness indenter penetrated to the same depth in all groups.

We used bars, test specimens with a simple shape, and applied unidirectional force. We recognize that these characteristics do not fully reproduce clinical situations, which have more complex shapes and different force orientations. However, the use of simple shapes and unidirectional force allowed us to achieve our objective, namely to analyze the influence of the printing angle on the mechanical properties of the tested material. For methodological reasons, only a single resin was tested in this study. Therefore, it was not possible to compare whether the behavior of different materials can be influenced by the print orientation, and the data obtained should not be universally extrapolated. In addition, we did not apply an aging period. Several authors suggest that aging test specimens can contribute to a decrease in their flexural strength. It is interesting to note that the behavior of resins after artificial aging tested seems to be influenced by the type of resin [18,21,27]. Therefore, it is suggested to test the behavior of resin after aging.

Several factors such as the type and composition of resins, printing technology, layer thickness, the degree of polymerization, the distance between layers, the intensity of the light source, and different post-polymerization techniques, among others, influence the mechanical and physical properties of the material to be printed. Thus, other comparisons beyond those already performed in this study are difficult to discuss. Given so many variables that interfere with the additive manufacturing process, this field remains fertile for additional scientific investigation.

Conclusion

Using a 0° printing angle results in the best bending resistance and lowest roughness, which may contribute to better clinical behavior.

Authors' Contributions

NVQ	https://orcid.org/0000-0002-0617-3733	Investigation, Writing - Original Draft and Writing - Review and Editing.
ASM	https://orcid.org/0000-0002-0600-4286	Investigation, Writing - Original Draft and Writing - Review and Editing.
ANGA	https://orcid.org/0000-0003-4554-7440	Methodology, Formal Analysis, Writing - Review and Editing and Supervision.
VMB	https://orcid.org/0000-0002-2633-010X	Conceptualization, Methodology, Formal Analysis, Writing - Review and Editing and Supervision.
All authors declare that they contributed to critical review of intellectual content and approval of the final version to be published.		

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None.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability

The data used to support the findings of this study can be made available upon request to the corresponding author.

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