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Influence of Printing Angulation on the Flexural Strength of 3D Printed Resins: An In Vitro Study

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Featured Application: Flexural strength is a fundamental parameter for long-lasting restorations. Printing angulation affects the flexural strength differently depending on the 3D printed material.

Abstract: This study compared the flexural strength of various 3D printed resins fabricated at different building angles (0°, 45°, and 90°). Four groups of resins were tested: Varseo Smile Teeth (Bego GmbH & Co., Bremen, Germany), V-print C&B Temp (Voco GmbH, Cuxhaven, Germany), Bego Triniq (Bego GmbH & Co. KG, Bremen, Germany), and Sprintray Crown (SprintRay, Los Angeles, CA, USA). A digital light processing 3D printer (Asiga MAX UV, NSW, Sydney, Australia) was used to fabricate the samples at the specified build angles (0°, 45°, and 90°) in accordance with the ISO 4049:2019 standard. Flexural strength was measured using a universal testing machine (Instron 5567; Instron Ltd., Norwood, MA, USA), and fracture analysis was performed using a scanning electron microscope (Jeol JSM-6060LV, Tokyo, Japan). Statistical analysis was carried out using the Statistical Package for the Social Sciences (SPSS, version 26; IBM Corp., Chicago, IL, USA). Means and standard deviations were calculated for each group, and statistical differences were assessed using one-way ANOVA followed by the Bonferroni post hoc test ($p < 0.05$). All tested resins exhibited high flexural strength values. The maximum flexural strength was observed in the 0° printed samples (137.18 ± 18.92 MPa), while the lowest values were recorded for the 90° printed samples (116.75 ± 24.74 MPa). For V-print C&B Temp, the flexural strength at 90° (116.97 ± 34.87 MPa) was significantly lower compared to the 0° (156.56 ± 25.58 MPa) and 45° (130.46 ± 12.33 MPa) orientations. In contrast, Bego Triniq samples printed at 45° (148.91 ± 21.23 MPa) demonstrated significantly higher flexural strength than those printed at 0° (113.37 ± 31.93 MPa) or 90° (100.96 ± 16.66 MPa). Overall, the results indicate that the printing angle has a significant impact on the flexural strength of the materials, with some resins showing lower strength values at the 90° build angle.

Keywords: 3D printing; additive manufacturing; flexural strength; printable resins; fixed prosthodontics

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1. Introduction

According to ISO/ASTM 52900:2023, additive manufacturing is the process of joining materials to make parts from 3D model data, usually layer by layer, as opposed to subtractive manufacturing and formative manufacturing methodologies [1].

Three-dimensional printing has been used in prosthodontics to produce master casts, patterns for fixed dental prostheses, interim restoration, removable dentures, and custom trays [2]. Today, since the development of new materials, the integration of 3D printing techniques has made it possible to apply additive manufacturing to the fabrication of definitive restorations, reducing time and costs [3]. In fact, 3D printable materials have a lower cost compared to milled ones, lower production time, and lower waste of materials [4].

Different factors can influence the quality and characteristics of the printed restorations, such as resin type [5,6], 3D printer [7–9], printing parameters [10,11], and post-curing procedures [12]. In fact, all these parameters can influence accuracy in terms of the internal fit of the restorations [13], surface roughness [14], and mechanical properties [15,16].

The printing orientation is still a controversial aspect in the literature [17–21].

In fact, even if printing at a 90° printing orientation allows an optimization of the printing procedure, reducing printing time and allowing the production of multiple objects compared to the 0° printing orientation, it seems to lead to the production of restorations with inferior mechanical properties [17,18,21].

Different studies reported the highest flexural strength at 0°compared to 45° or 90° [17–19], while two studies demonstrated higher values when the specimens were printed vertically (90°) [12,20]. Kebler et al. [21] reported that the three-point bending test induces stresses in the specimens, which can cause the low-strength interfaces between the 2D layers to delaminate before the 2D layers fracture. The observed failure between the layers at the vertical printed samples tends to be more catastrophic because of fractures than the horizontal printed ones, but the most important factor is played by the different printable materials. The mechanical performance of resin composites is also related to their chemical formulation. The characteristics of the co-monomers involved will determine the hydrophilicity, mobility, and kinetic parameters [22,23]. Additionally, flexural strength can be strongly affected by the reinforcement of 3D-printed resin by the addition of fillers. It was reported that nanofillers improved the strength of 3D-printed resin according to their type, size, and concentration [24,25]. In particular, the addition of glass silica and zirconia nanoparticles to 3D printable resins seems to enhance the mechanical properties of these materials.

The wear resistance is enhanced by the addition of glass silica nanoparticles that create a stronger microstructure [26,27]. The risk of wear, chipping, or fractures over time is lowered by the reinforcement, resulting in more durable dental restorations. The enhanced properties obtained with the addition of nanoparticles are a promising approach for improving the mechanical properties of dental resins [28].

On the other hand, the high concentration of fillers and nanofillers might have adverse effects on flexural strength due to the clustering of the particles, which clinically might be the starting point of a line of fracture [29].

Several studies evaluated crown and bridge 3D printed restorations in both in vivo and in vitro conditions [30–32]. However, recently, an increasing number of 3D-printed resins have been presented in the market for crown and bridge restorations with promising results. The flexural strength analysis of these new materials can be fundamental to better understanding their clinical indications before their wide clinical use.

The aim of this study is to assess and compare flexural strength values of different 3D-printed materials at different built inclinations.

The null hypothesis was that resin type and the printing angle have no statistically significant influence on flexural strength.

2. Materials and Methods

In this study, 120 rectangular specimens of different 3D-printed resin-based materials, having dimensions of 25 × 2 × 2 mm, were fabricated according to the ISO 4049:2019 standard, as shown in Figure 1 [33,34].

Four different 3D-printable resins were used (n = 30): Varseo smile teeth (Bego GmbH & Co., Bremen, Germany), V-print C&B temp (Voco GmbH, Cuxhaven, Germany), Bego Triniq (Bego GmbH & Co. KG, Bremen, Germany), and Sprintray Crown (SprintRay, Los Angeles, CA, USA), as described in Table 1. Each group was divided into three subgroups according to the printing orientation: 0°, 45°, or 90° (n = 10), as shown in Figure 2.

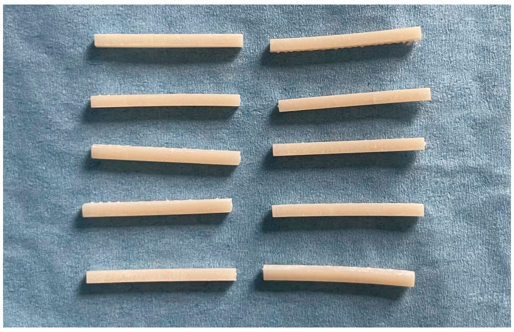


Figure 1. 3D-printed samples fabricated according to the ISO 4049:2019 standard [34].

Table 1. 3D-printable resins tested in the present study.

Name	Manufacturer	Material	Batch No.
Bego Varseo smile teeth	Bego	4,4-Isopropylidenediphenol, ethoxylated 2-methylprop-2enoic acid. Silanized dental glass, methyl benzoylformate, diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide. Inorganic fillers (particle size 0.7) 30–50% of the mass.	600,850
V-Print c&b temp	Voco	UDMA Bis-EMA TEGDMA 50–100% 25–50% 5–10%	6898
Bego Triniq	Bego	4,4-Isopropylidenediphenol, ethoxylated 2-methylprop-2enoic acid, Benzeneacetic acid, alpha. -oxo-, methyl ester; diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide.	2,212,091
Crown	SprintRay	4,4'isopropylidiphenol, ethoxylated and 2methyl prop2enoic acid. Silanized dental glass, methyl benzoylformate, diphenyl (2,4,6trimethyl benzoyl) phosphine oxide. Total content of inorganic fillers (particle size 0.7 µm) is 30–50% by mass.	600,850

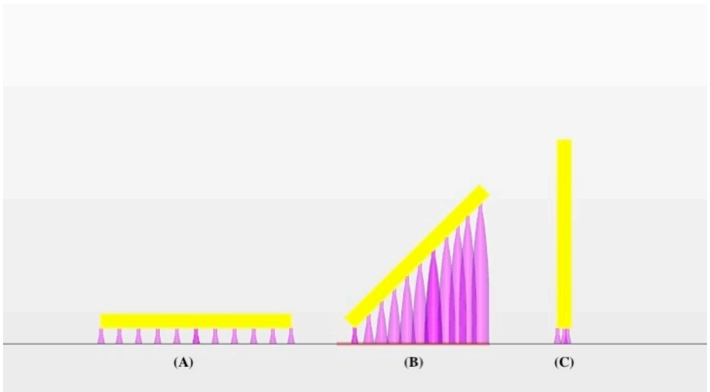


Figure 2. The printing orientation is reported with different letters: (**A**) = 0°, (**B**) = 45°, (**C**) = 90°. Yellow represents the samples, while the supports generated by the software are in purple.

2.1. Sample Fabrication

CAD software MESHMIXER 3.5 (Autodesk, San Francisco, CA, USA) was used to design an STL file of a rectangular specimen of accurate dimensions that was sent to the DLP printer Asiga MAX UV (wavelength = 385, pixel resolution = 62; NSW, Hawthorn, Australia) and printed at a 0°, 45°, and 90° build orientation for each of the tested resin. Then, Liquidtech BT was used to clean the samples for 20 min using the BB Wash machine (Meccatronicore S.R.L., Pergine Valsugana, TN, Italy). All the samples were polymerized with a BB cure machine (Model MTC-BB-CURE-COMPACT, Meccatronicore S.R.L., TN, Italy) curing unit for 40 min. Then, a slow-speed rotatory instrument was used to remove the specimen's support structures, and, subsequentially, all samples were polished with a 600-grit sandpaper, measured using a digital caliper with ±0.02 mm accuracy. Before performing three-point flexural strength tests, the samples were stored in distilled water for 24 h.

2.2. Flexural Strenght Analysis and Fracture Analysis

A universal testing machine (5567 Universal Testing Machine; Instron Ltd., Norwood, MA, USA) was used to carry out the three-point flexural strength tests. Each specimen was placed on circular support beams with a 20 mm span, as reported in Figure 3.

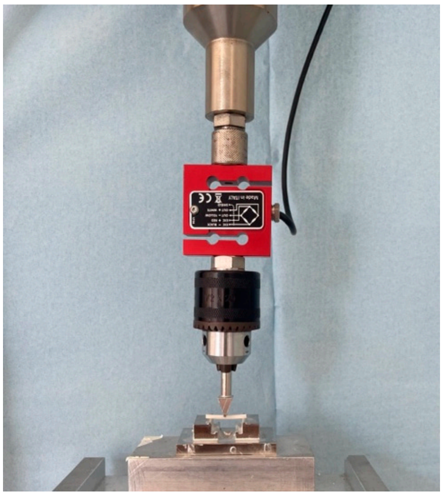


Figure 3. Universal machine for three-point bending test.

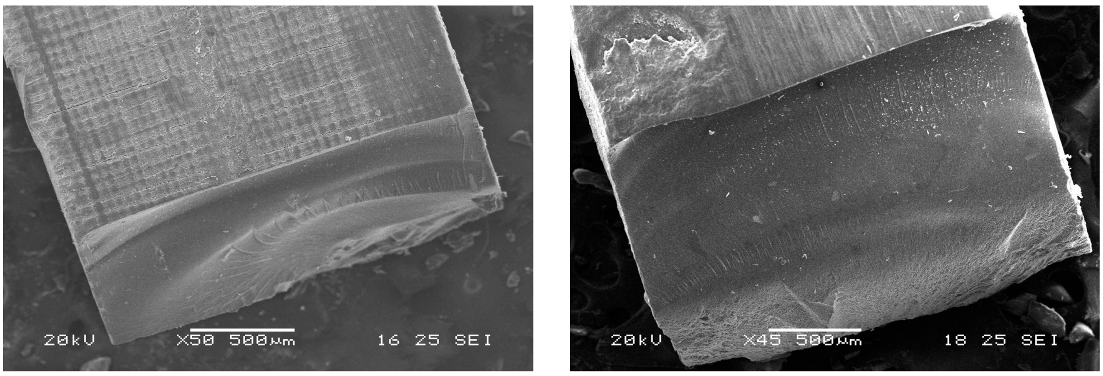
The loading force was applied to the center of each specimen at a crosshead speed of 5 mm/min. For each specimen, the fracture load was registered. The same operator performed all the tests (G.V.).

Flexural strength was calculated using the following formula and reported in tables in Megapascal (MPa):

$$FS = (3\ P\ L)/(2\ b\ d^2)$$

FS: flexural strength, P: maximum load, L: span length (20 mm), b: width, and d: thickness.

The fractured surface of the samples was further analyzed with a scanning electron microscope (Jeol, Jsm-6060LV Scanning Electron Microscope) to determine the fracture origin. Photos of the fractured surface are reported in Figure 4.



(**a**) (**b**)

Figure 4. SEM images of the fractured surface for V-print C&B temp (**a**) sample printed at 90°; (**b**) sample printed at 0°.

2.3. Statistical Analysis

Statistical Package for the Social Sciences (SPSS) software, version 26 (IBM SPSS statistics, v.26, Inc., Chicago, IL, USA) was used for Statistical analysis. Means and standard deviations were calculated for each group. Statistical differences were tested with an ANOVA test and a Bonferroni test as post hoc. ($p < 0.05$). A priori sample size calculation was performed (for each group) based on the general formula $N = (Z_\alpha + Z_\beta)^2 \times 2 \times (S)^2/D^2$, where N = sample size per group, Z_α = value of type I error, Z_β = value of type II error, S^2 = variance, and D = difference to detect. Assuming 20 MPa as the expected standard deviation and assuming to search for a statistically significant difference higher than the S.D. (i.e., 30 MPa), the needed sample size per group was 9.9 samples, with an alpha error of 0.05 and a beta error of 0.20.

3. Results

Table 2 reports the mean and standard deviation for each tested material independently from the printing orientation. No statistically significant difference was found between the tested samples.

Table 2. Mean flexural strengths (Mean), standard deviations (SD), and significant differences (Sign.) for each material.

Material	N	Mean	SD	Sig. $p < 0.05$
Bego Varseo Smile teeth	30	133.27	24.64	A
V-print C&B temp	30	134.66	30.12	A
Bego trinQ	30	121.08	31.14	A
Sprintray Crown	30	120.53	26.62	A

Legend: N: number of samples for each group, SD: standard deviation, Sig.: significant differences. Same letters per table denote no statistically significant differences ($p > 0.05$).

Two-way ANOVA tests indicate that both the material and the inclination have a significant effect on the flexural strength, and that there is a significant interaction between the two factors, as reported in Table 3.

Table 3. Two-way ANOVA results.

	sum_sq	df	F	P
3D-printed material	9099.07	4.00	4.01	0.00
Inclination	4894.23	2.00	4.31	0.02
C (material):C (inclination)	21,149.54	8.00	4.66	0.00
Residual	76,650.36	135.00		

Legend: sum_sq: sum of squares, dF: degree of freedom, F: f-value, P: *p*-value.

Table 4 reports the mean and standard deviations for each resin group depending on the printing orientation. For V-print C&B temp, flexural strength values were statistically significantly lower when the samples were printed at 90° (116.97 ± 34.87) angulation with respect to 0° (156.56 ± 25.58) or 45° (130.46 ± 12.33). In contrast, for Bego trinQ (Bego GmbH & Co., Bremen, Germany), the samples printed with an inclination of 45° (148.91 ± 21.23) showed statistically significantly higher values than the one printed at 0 (113.37 ± 31.93) or 90° (100.96 ± 16.66) No statistically significant difference was found for Bego Varseo Smile (Bego GmbH & Co., Bremen, Germany) or Sprintray Crown (SprintRay, Los Angeles, CA, USA).

Table 5 reports the mean and standard deviations from each of the 3D-printing degrees independently from the resin type. Samples printed at a 90° orientation registered statistically significantly lower values of flexural strength compared to 0° or 45°.

Table 4. Mean flexural strengths (Mean), standard deviations (SD), and significant differences (Sign.) for Bego Varseo smile teeth, V-print C&B temp, Bego Triniq, and Sprintray Crown.

Materials	Inclination	Mean	SD	Sig. $p < 0.05$
Bego Varseo Smile teeth	0°	132.52	35.25	A
	45°	133.04	22.12	A
	90°	134.24	14.94	A
V-print C&B temp	0°	156.56	25.58	A
	45°	130.46	12.33	A
	90°	116.97	34.87	B
Bego trinQ	0°	113.37	31.93	A
	45°	148.91	21.23	B
	90°	100.96	16.66	A
Sprintray Crown	0°	110.41	36.13	A
	45°	136.33	15.38	A
	90°	114.85	17.72	A

Legend: N: number of samples for each group, SD: standard deviation, Sig.: significant differences. Same letters per table denote no statistically significant differences ($p > 0.05$).

Table 5. Mean flexural strengths (Mean), standard deviations (SD), and significant differences (Sign.) for printing orientation.

Inclination	N	Mean	SD	Sig. $p < 0.05$
0°	40	137.19	18.92	B
45°	40	128.21	36.37	B
90°	40	116.75	24.74	C

Legend: N: number of samples for each group, SD: standard deviation, Sig.: significant differences.

4. Discussion

Flexural strength is one of the fundamental characteristics of a restorative material, and high values will reduce the risk of restoration fractures under the masticatory forces [33].

Due to the results obtained in the present in vitro study, the null hypothesis was partially rejected since no statistically significant differences were reported on the flexural strength between the studied 3D-printed resin groups, but they were found for the built angles evaluated. All tested samples showed high values of flexural strength, higher than the minimum requirement of ISO 4049:2019 standard [34]. The mean value of flexural strength for each resin was double the minimum requirement of flexural strength reported in ISO 10477:2020 standard [35] of 50 Mpa for interim restorations. Thus, as reported by a previous study by Park et al. [36], all the tested materials can be considered suitable for performing temporary restorations.

Even if the 90° printing orientation allows an optimization of the printing procedure, the results obtained suggest that it produces lower values of flexural strength compared to 0° or 45° [37].

As shown in Table 4, printing angulation plays a fundamental role for some of the tested materials. However, Varseo smile teeth (Bego GmbH & Co., Bremen, Germany) and Sprintray Crown (SprintRay, Los Angeles, CA, USA) flexural strength values seem to be not statistically influenced by the printing angulation. Instead, for V-print C&B temp (Voco GmbH, Cuxhaven, Germany), flexural strength values were statistically significantly lower when the samples were printed at a 90° angulation respect to 0° or 45°, while for Bego Triniq (Bego GmbH & Co. KG, Bremen, Germany), samples printed with an inclination of 45° were statistically significantly stronger than the ones printed at 0 or 90°. Therefore, when selecting the material for future restorations, clinicians and technicians should take into consideration that the printing angulation, for some materials, has important effects on the durability of the future restoration.

The analysis of the fractured surface revealed differences in the fracture mode. Figure 4a,b reports examples of fractured surfaces at SEM for V-print C&B temp where the difference between samples printed at 0° or 90° was statistically significant and more evident than in other groups. Figure 4a shows the fracture of one of the samples printed at 90°: it is possible to observe a fracture with minimal plastic deformation of the material and typical cracks that extend radially in different orientations. It is also possible to see a layering structure on top of the sample due to the 90° printing orientation. In Figure 4b, a 0° printed sample is shown: observation under the microscope reveals significant plastic deformation before fracture of the sample. The fractured surface is smooth, compared to Figure 4a, and so-called beach lines or conchoidal lines are observed as a macroscopic feature. A typical striped pattern called striation is observed. The fatigue stripes are perpendicular to the direction of advancement of the crack and slightly concave compared to the initiation point. On top of the sample, it is possible to observe the layering structure due to the 0° printing orientation. It can be speculated that a 90° printing orientation probably leads to layers parallel to the load direction, resulting in an easier delamination of the junction between the layers when the tensile stress is generated during force application [37].

In Table 1, all the components of each resin are reported: in V-Print c&b temp (Voco GmbH, Cuxhaven, Germany) and Bego Triniq (Bego GmbH & Co. KG, Bremen, Germany), no fillers are specified by the manufacturer, while Bego Varseo smile teeth (Bego GmbH & Co. KG, Bremen, Germany) contains 30–50% of inorganic fillers in the mass and the same is reported for Crown Spritray (SprintRay, Los Angeles, CA, USA). For dental composite, it has been demonstrated that a higher filler component shows higher values of flexural strength [38,39]. Probably, the high values of flexural strength obtained by the tested materials are caused by their high filler load [40]. However, it must be taken into consideration that filler size and distribution can influence the viscosity of the composite as well [41]. The viscosity of resins should be as low as possible to allow a good flow of the monomer on the polymerized layer during the additive manufacturing process [42]. If this process does not take place completely due to the high viscosity of the resin, the final 3D-printed object can incorporate voids, incomplete curing, or processing defects. Different resins will flow differently during the SLA/DLP printing process, and it could be speculated that different printing angulations can affect the recoating process differently for each of the tested materials, leading to small voids in different parts of the 3D-printed object. When the loading force is applied, the voids will cause a different premature break of the sample depending on their position between the layers [43].

The weakest links in a 3D-printed object are demonstrated to be the interlayers, since they can be separated easily by interfacial shear loads [44]. In this paper, the specimens were printed at a 50 µm thickness. As reported by Dizon et al. [45], different printing thicknesses will influence the flexural strength due to the fact that the total area of the interface between the layers is directly dependent on the first, so further tests should be carried out to assess the flexural strength of these materials at different thickness orientations.

Another important factor to consider is the post-processing protocol applied to the specimens, which determines the resin polymer's degree of conversion. A low degree of conversion results in inferior mechanical properties [46]. In the present research, the same post-processing protocol was applied to all the specimens to standardize the protocol, but this can be more suitable for some of the tested resins and less favorable for others, resulting in different degrees of conversion between the specimens and, consequentially, in different flexural strength values [47]. It should be noted that the flexural strength values obtained by these recently released 3D-printable materials tested in the present study are higher than the ones obtained in previous papers, highlighting a rapid evolution of additive manufacturing materials [16,37,48]. Because of the high values of flexural strength obtained from this in vitro study, higher resistance under masticatory forces and higher wear resistance are expected. Clinically, 3D-printable resins could be proposed for definitive or long-term restorations such as onlays, inlays, or single crowns in patients without signs of parafunctional activities. The use of 3D-printed materials for fixed restorations could fasten the production process, lower its cost, and decrease the waste of materials compared to subtractive manufacturing [4].

Mechanical properties can be enhanced by the reinforcement of the printed resin, but the latter can affect resin color, fluidity, or light penetration depth, so these new materials should be evaluated carefully under in vitro conditions [48].

This in vitro study has limitations. As stated before, to standardize the procedure, the same printing thickness and the same post-processing protocol have been used for all the samples, but different parameters should be investigated as well. Additionally, the samples were stored in distilled water only for 24 h before the flexural strength test. Long-term studies or the use of thermocycling to imitate resin aging are needed to better understand the changes in flexural strength over time.

In order to validate the materials for clinical use for medium- and long-term restorations, additional tests should be carried out, such as surface hardness tests, impact strength tests, and color stability evaluations, but mostly dimensional stability tests.

5. Conclusions

This in vitro study examined the flexural strength of various 3D-printed resins at different build angles (0°, 45°, and 90°). It found significant differences in flexural strength based on the build angle, although some resin groups showed no notable variation. All materials surpassed ISO standards for flexural strength, but the 90° orientation led to lower strength for some resins compared to 0° and 45°. This fact highlights the need to consider build angles when selecting resins for dental restorations, as they significantly impact durability. The fracture surface analysis revealed differences in fracture modes, indicating that printing orientation affects the tensile stress distribution and delamination potential. While the results suggest that 3D-printed resins are suitable for long-term dental use, further research is essential. Overall, the study showcases advancements in 3D-printable materials that could revolutionize dental restoration production by reducing costs, material waste, and time.

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