

Article

Mechanical Assessment of CAD/CAM Fabricated Hybrid Ceramics: An In Vitro Study

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Abstract: The current study aimed to compare the mechanical properties of CAD/CAM fabricated hybrid ceramic restorative materials. The current study assessed the mechanical properties of additively and subtractively manufactured CAD/CAM fabricated hybrid ceramic by conducting flexure strength test, compressive strength test, and Vickers hardness test. Flexural samples were subjected to a three-point bending test using a universal testing machine until the samples showed fracture. Moreover, samples for the compressive strength test were subjected to compression tests using a universal testing machine until samples were fractured. Samples for the Vickers hardness was tested using the Vickers hardness testing machine to determine the sample's hardness values. There were significant differences ($p = 0.0001$) were observed among the additive and subtractive groups in terms of flexure strength and compressive strength test. Regarding the Vickers hardness test, significant differences ($p = 0.0001$) were observed between the polished and unpolished groups in additive manufacturing. However, no significant ($p = 0.681$) differences were observed in the subtractive manufacturing technique. The subtractive group achieved ISO specifications in terms of flexural strength and was superior to additive groups in hardness while exhibiting lower performance in compressive strength. Moreover, printing orientation had a significant influence on the performance of additive groups. Flexural strength and hardness were improved when the printing orientation was in alignment with the direction of load (90°) while compressive strength was improved when the printing orientation was perpendicular to the direction of load (0°).

Keywords: 3D printing; hybrid ceramics; additive manufacturing; CAD/CAM; subtractive manufacturing



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1. Introduction

In the recent era, restorations using computer-aided design and computer-aided manufacturing (CAD/CAM) became widely accepted due to the elimination of labor and time consumption [1]. CAD/CAM could minimize the errors in impression-taking, modeling, and casting procedures compared to the traditional technique [2]. CAD/CAM systems generally consist of two methods: the additive method and the subtractive method. In the additive method or three-dimensional (3D) printing method, layers of resin, porcelain, or metal materials are added by layers in the restoration manufacturing process. This procedure is cost-effective and minimizes waste [3]. On the other hand, the subtractive or milling method functioned by cutting prefabricated blocks into the anticipated shape, which led to

additional costs of milling tools and wastes compared to 3D additive manufacturing [3,4]. Due to the invention of the additive method, the replacement of prostheses became easier as data could be digitally stored, which could also lead to a reduction in appointment numbers and time [3].

An imperative substitute for direct restoration is a CAD/CAM fabricated hybrid ceramic with a subtractive manufacturing method [5]. Hybrid ceramics became popular among patients due to the appropriate aesthetic demand. Moreover, improved mechanical and physical properties of the hybrid ceramics make them acceptable among patients and dentists [5,6]. Compared to the direct manufacturing method, hybrid ceramics decrease the fabrication time and provide a dimensionally accurate restoration [7]. Prior reports have indicated that the incorporation of ceramic and polymer phases in these materials imparts stability, flexural strength, elasticity, and hardness comparable to that of natural tooth structure [8,9]. Even though additive technology has become popular in clinical applications in recent years, it initially had restricted application in the field of dentistry due to manufacturing accuracy, durability, processing time, and cost. However, more precise 3D printing devices, advanced printing accuracy, and a variety of materials make this technology more acceptable to clinicians and clinical applications [10,11]. Moreover, 3D additive technology possesses the ability to fabricate complex shapes, reduces waste of materials, and is cost-effective compared to the subtractive technique [9].

Three-dimensional print manufacturing has some limitations in clinical application including roughness values, aesthetic appearance, dimensional accuracy, and wear resistance [10–15].

The choice of printing orientation or build direction is a crucial first step in additive manufacturing processes. Involved time in the production process is contingent upon the printing orientation. The number of layers employed in the fabrication of the component varies in different directions. The chosen construction orientation should optimize the support area, therefore reducing the required time for finishing and polishing [16]. The reduction in size between the layers is also influenced by the direction of construction and hence the orientation of the layers [17]. Moreover, the orientation of the layers directs the mechanical characteristics of the heterogeneous printed material [17,18]. Nevertheless, considering the correlation between layer orientation and load direction, choosing a uniaxial direction was more suitable for gaining a fundamental comprehension of the several processes by which defects develop in the material towards structural failure [17].

Alharbi et al. [17] investigated the impact of layer orientation on the mechanical characteristics of a new dental restorative material produced by three-dimensional (3D) printing. He proved that the layer orientation was found to influence the compressive strength of the material. Conversely, Kebler et al. [19] examined the effect of printing direction on the mechanical properties of 3D-printed resin-based composites. They revealed that the effects of printing direction were material-dependent. An analysis of how various parameters impact the mechanical properties of printed materials can enhance the quality and consequently the performance of the manufactured product.

Surface characteristics, including roughness and gloss, have a substantial impact on the clinical result of dental restorations, making polishability a crucial attribute for dental materials [20]. Improperly finished and polished surfaces are more prone to plaque buildup, wear, heightened risk of staining and secondary caries, and may also contribute to increased gingival inflammation, which may result in diminished clinical success [20]. Furthermore, restorations featuring smoother surfaces provide greater comfort for the patient and enhance their aesthetic value [20].

There is insufficient evidence in the literature related to CAD/CAM fabricated hybrid ceramics fabricated with additive manufacturing and subtractive manufacturing in the field of dentistry.

2. Literature Review

Currently, glass ceramics and hybrid ceramics are the two primary types of machinable aesthetic materials involved in the manufacturing of CAD/CAM restorations [21]. Advancements in composite technology have greatly enhanced hybrid ceramics over the last ten years [21]. These hybrid ceramics have been extensively used in CAD/CAM systems to fabricate indirect restorations, including inlays, onlays, veneers, crowns, and bridges [21].

Launched in 2000, the Paradigm MZ100 (3M ESPE, USA) was the first resin composite block designed for CAD/CAM systems. The Paradigm MZ100 block is composed of a direct resin composite and includes 85 wt.% ceramic fillers consisting of ultrafine zirconia and silica [22]. The flexural strength, flexural modulus, compressive strength, and diametral tensile strength are, respectively, stated to be 146 MPa, 12.7 MPa, 524 MPa, and 114 MPa [22]. The Lava Ultimate block was subsequently developed by 3M ESPE using a resin nano ceramic substance that consists of about 80 wt.% zirconia–silica nano ceramic fillers [23]. The flexural strength (204 MPa) showed considerable enhancement in comparison to Paradigm MZ100 [24]. Furthermore, GC Corporation, Japan, introduced Cerasmart as a hybrid ceramic block that incorporates 75 wt.% of nano-ceramic particles within a resin matrix that is intensively cross-linked, similar to the Lava Ultimate block which had a noteworthy flexural strength of 231 MPa [24].

These novel composite block materials, despite having variations in composition and curing conditions, are produced using traditional filler-resin mixing composite technology [25]. The Polymer-Infiltrated-Ceramic Network technology was introduced by VITA Zahnfabrik, Germany, to create Vita Enamic, a genuinely hybrid ceramic designed for CAD/CAM restorations [26]. An initial formation of a porous ceramic network (86 wt.%) was followed by its infiltration by polymeric resins, therefore offering a novel approach to enhance the loading capacity of fillers. In comparison to composite block materials produced by combining fillers and polymeric resins, Vita Enamic demonstrated notably greater modulus of elasticity (30 ± 2 GPa) and hardness (2.5 GPa) [26]. In addition, determining the mechanical characteristics of hybrid ceramic material flexural strength plays an imperative role which provides information about the ability of load endurance when tensile and compressive stress are combined [10,12].

Most of the existing CAD/CAM technologies in dentistry are founded on subtractive design. The subtractive method employs a cutting tool to mechanically abrade the material and obtain the intended shape in accordance with computer-guided instructions. Additive manufacturing, or 3D printing, is the method of constructing materials layer by layer directly from 3D digital raw data [3,27,28]. The advantages of additive manufacturing over conventional subtractive (milling) processes are numerous. The additive technology enables the production of an object independent of its numerical and dimensional complexity [29]. A 40% reduction in material waste is achievable, and it is possible to produce features that are finer than the size of the milling bur. A growing body of research indicates that additive manufacturing methods are being increasingly used in multiple dental fields, including the production of dental models, surgical guides, and occlusal devices [30–32]. Nevertheless, the application of this technique in the field of prosthodontics has not been sufficiently addressed. Moreover, the impact of different printing orientations and their consequences on the ultimate quality and mechanical characteristics of the printed restorations has not been well examined.

Recently, we reported a novel CAD/CAM resin composite block named Shofu with high mechanical properties intended to evaluate its flexural, compressive, and hardness properties. Therefore, the current study aimed to compare the mechanical properties of hybrid ceramic restorations fabricated by CAD/CAM technology utilizing subtractive and additive techniques in different printing orientations. The null hypothesis examined was that there would be no significant differences in the flexural, compressive strength, and hardness of hybrid ceramic restorations fabricated by CAD/CAM technology utilizing subtractive and additive techniques in different printing orientations.

3. Materials and Methods

3.1. Sample Size Calculation

Concerning flexural and compressive strength tests, the sample size of 12 specimens for each group for the one-way ANOVA analysis was set according to ISO 6872 [33]. However, for the Vickers hardness test, the sample size of 15 specimens for each group for the paired *t*-test was set according to ISO 6872 [33].

3.2. Study Design

The current *in vitro* study was approved by the Standing Committee of Bioethics Research (SCBR) at Prince Sattam bin Abdulaziz University (SCBR-123/2023). This study was conducted to assess the mechanical properties of CAD/CAM fabricated hybrid ceramics materials by subtractive and additive techniques. Additive samples were subdivided into 0°, 45°, and 90° printing orientations to analyze layering direction impact, as seen in Figure 1. The ISO 4049 standard [34] was used for sample preparation and testing of flexural strength, the ADA Specification No. 27 [35] was used for sample preparation and testing of compressive strength, and established literature protocols were used for hardness testing in this study.

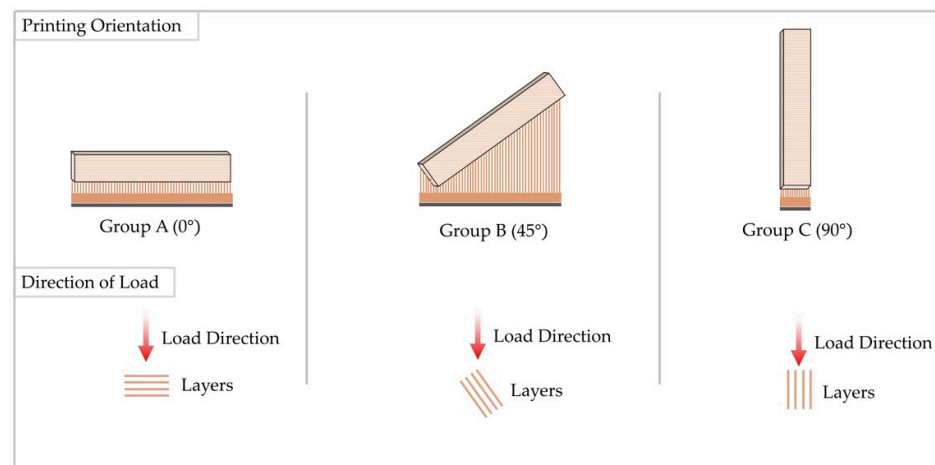


Figure 1. Schematic charts illustrate layers deposition of 3D-printed groups and the direction of load on the printed layers: group A with 0° printing orientation; group B with 45° printing orientation; group C with 90° printing orientation.

3.3. Samples Preparation

Bar-shaped specimens (25 mm × 2 mm × 2 mm) were designed using Fusion 360 software per ISO specifications [16] to assess flexure strength. This design was saved in Standard Tessellation Language (STL) format and subsequently transferred to CAD/CAM milling and the 3D printer to fabricate the specimens. Milled samples were prepared using designed STL files that were processed in Ceramill Mind CAD software (V2.4-7437, Amann Girrbach AG, Mäder, Austria). A total of 12 samples were milled using a 5-axis milling machine (Ceramill Motion 2, Amann Girrbach AG, Mäder, Austria) from a hybrid ceramic disc (SHOFU DISK HC, SHOFU Inc., Kyoto, Japan). STL files were imported into the printer software (AsigaComposerV1.2 software, Asiga, Alexandria, Australia), and 12 samples for each orientation were printed using a desktop 3D printer (Asiga Max UV printer, Alexandria, Australia). CROWNTEC resin (Saremco Dental AG, Rebstein, Switzerland) and NextDent C&B MFH resin (vertex dental, Soesterberg, The Netherlands) were used to make the 3D-printed samples. All flexural samples were wet ground with 320 abrasive paper (SiC grinding paper, Buehler, Germany) and stored in water at 37 °C until further testing. Moreover, Cylinder specimens (4 mm diameter, 6 mm height) were designed using Fusion 360 software as per ADA specifications, saved in STL format, and fabricated using CAD/CAM milling and 3D printing to assess compressive strength. Twelve samples were

milled and printed for each group utilizing the previously described fashion. Materials and finishing protocol utilized in the current study are described in Table 1.

Table 1. Materials utilized in the current study.

Material	Description	Composition	Polishing Protocol	Manufacturer	Batch Number
Shofu Disc HC	CAD/CAM hybrid ceramic disc	Urethane dimethacrylate, triethylene glycol dimethacrylate, silica powder, fine particulate silica, zirconium silicate, colorant		SHOFU Inc., Kyoto, Japan	416581
Saremco print CROWNTEC	3D printing resin	bisphenol A diglycidyl methacrylate ethoxylated, trimethylbenzoyldiphenylphosphine oxide	I. Trimming with dark grey coarse grit polisher (No. 0426) for 1 min II. Finishing with brown medium grit polisher (No. 0427) for 1 min III. Polishing with light grey fine grit polisher (No. 0428) for 1 min	Saremco Dental AG, Rebstein, Switzerland	E394
Nextdent C&B MFH	3D printing resin	Methacrylic oligomers, methacrylate monomer, inorganic filler, phosphine oxides, pigment		NextDent, Soesterberg, The Netherlands	WX131N54

For Vickers hardness samples, a cylindrical specimen shape (10 mm diameter, 12 mm height) was designed by using Fusion 360 software, and then the STL file of this design was imported to the milling machine to fabricate the cylindrical sample, as previously described. A total of six disc-shaped samples (10 × 2 mm) were cut from the cylinder using a low-speed precision saw to conserve the material. Then, three of those samples were finished and polished according to the manufacturer's instructions. Additionally, disc-shaped specimens (10 mm diameter, 2 mm height) were 3D-printed utilizing the previously described fashion. A total of six samples per printing orientation were produced, with three samples in each group that were finished and polished according to the manufacturer's instructions.

3.4. Samples Testing

Flexural samples were subjected to a three-point bending test using a universal testing machine (Instron 5965, Canton, MA, USA) at a crosshead speed of 1 mm/min until the samples showed the fracture. The maximum loads were recorded, and the flexural strength was calculated in MPa using computerized software (BlueHill software 3.22.1373. Norwood, MA, USA). However, samples for the compressive strength test were subjected to the compression test using a universal testing machine (Instron model-5965) at a crosshead speed of 1 mm/min until the samples fractured. The compressive strength values were recorded in MPa using computerized software (BlueHill software 3.22.1373. Norwood, MA, USA), as shown in Figure 2.

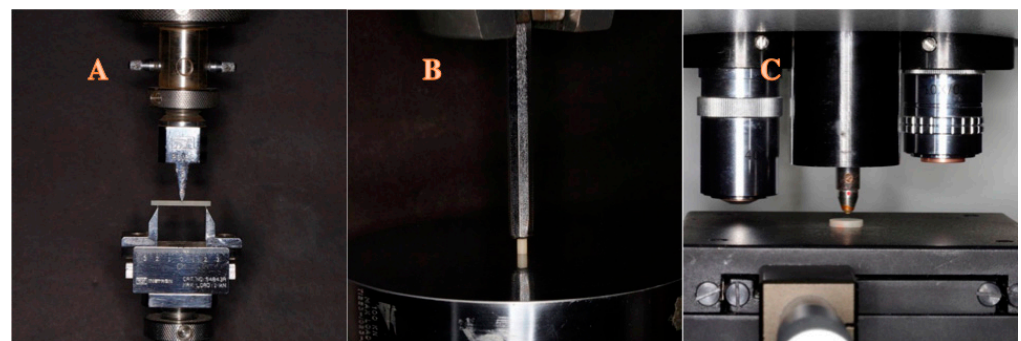


Figure 2. Images showing different types of specimens during the mechanical testing procedures. (A) Three-point bending test; (B) compressive strength test; (C) Vickers hardness test.

Samples for the Vickers hardness test were subjected to a load of 200 g at a 15 s dwell time by using a Vickers hardness testing machine (Nova 130, Maastricht, The Netherlands).

Five diamond-shaped indentations were obtained on each specimen, and then the diagonal lengths (D1 and D2) of a diamond shape were measured by a scaled microscope present within the Vickers hardness testing machine to determine the hardness results, as presented in Figure 2.

3.5. Statistical Analysis

The data obtained from testing the materials for flexural strength and compressive strength were subjected to statistical analysis with one-way ANOVA, while the Vickers hardness results were statistically analyzed with a paired *t*-test, using SPSS software, version 22 (IBM, Armonk, NY, USA). *p*-values less than 0.05 were considered statistically significant.

4. Results

4.1. Flexural Strength Test

A one-way ANOVA showed that there were significant differences ($p < 0.05$) among milled and three different degrees (0° , 45° , and 90°) of 3D-printed groups in the flexure strength test, as shown in Table 2. In addition, the post hoc Tukey HSD test also showed significant differences among all variables regarding the flexure strength (Table 3).

Table 2. Comparison of different groups in flexure strength.

Variables ($n = 12$)	Mean	SD	<i>p</i>
Milled	105.79	5.67	0.0001 *
3D-printed (0°)	32.43	1.27	
3D-printed (45°)	26.16	1.37	
3D-printed (90°)	41.73	1.07	

n; number of specimens, SD; standard deviation, 3D; three-dimension, $^\circ$; degree, *p*; *p*-value, *; significant difference ($p < 0.05$).

Table 3. Post hoc comparison among the groups for flexure strength.

Variables	MD	CI		<i>p</i>
		Lower	Upper	
Milled vs. 3D-printed (0°)	73.37	70.06	76.67	0.0001 *
Milled vs. 3D-printed (45°)	79.63	76.33	82.93	0.0001 *
Milled vs. 3D-printed (90°)	64.06	60.76	67.37	0.0001 *
3D-printed (0°) vs. 3D-printed (45°)	6.26	2.96	9.57	0.0001 *
3D-printed (0°) vs. 3D-printed (90°)	−9.30	−12.61	−5.99	0.0001 *
3D-printed (45°) vs. 3D-printed (90°)	−15.57	−18.87	−12.26	0.0001 *

MD; mean differences, CI; confidence interval, *p*; *p*-value, 3D; Three-dimension, vs.; versus, $^\circ$; degree *; statistically significant ($p < 0.05$).

4.2. Compressive Strength Test

A one-way ANOVA showed that there were significant differences ($p < 0.05$) among milled and three different degrees (0° , 45° , and 90°) of 3D-printed groups in the compressive strength test (Table 4). In addition, the post hoc Tukey HSD test also showed significant differences among all variables regarding compressive strength (Table 5).

Table 4. Comparison of different groups in compressive strength.

Variables ($n = 12$)	Mean	SD	<i>p</i>
Milled	319.97	3.67	0.0001 *
3D-printed (0°)	375.54	4.28	
3D-printed (45°)	330.11	3.19	
3D-printed (90°)	353.09	4.12	

n; number of specimens, SD; standard deviation, 3D; three-dimension, $^\circ$; degree, *p*; *p*-value, *; significant difference ($p < 0.05$).

Table 5. Post hoc comparison among the groups for compressive strength.

Variables	MD	CI		<i>p</i>
		Lower	Upper	
Milled vs. 3D-printed (0°)	−55.56	−59.75	−51.38	0.0001 *
Milled vs. 3D-printed (45°)	−10.14	−14.32	−5.95	0.0001 *
Milled vs. 3D-printed (90°)	−33.12	−37.31	−28.93	0.0001 *
3D-printed (0°) vs. 3D-printed (45°)	45.42	41.24	49.61	0.0001 *
3D-printed (0°) vs. 3D-printed (90°)	22.44	18.25	26.63	0.0001 *
3D-printed (45°) vs. 3D-printed (90°)	−22.98	−27.17	−18.79	0.0001 *

MD; mean differences, CI; confidence interval, *p*; *p*-value, 3D; Three-dimension, vs.; versus, °; degree, *; statistically significant (*p* < 0.05).

4.3. Vickers Hardness Test

Table 6 reveals the descriptive statistics of different tested groups. In addition, a paired *t*-test showed a significant difference in three different degrees (0°, 45°, and 90°) of 3D-printed groups (*p* = 0.0001) between the polished and unpolished versions except for the milled group (*p* = 0.681) (Table 7).

Table 6. Descriptive statistics of comparison of different groups in the Vickers hardness test.

Variables (<i>n</i> = 15)	Mean	SD
Milled unpolish	84.7933	1.78064
Milled polish	85.0333	1.14434
3D (0°) unpolish	3.5267	0.18696
3D (0°) polish	6.680	0.08619
3D (45°) unpolish	3.6600	0.14541
3D (45°) polish	8.4733	0.24339
3D (90°) unpolish	7.4133	0.28502
3D (90°) polish	12.4333	0.37544

n; number of specimens, SD; standard deviation, 3D; three-dimension, °; degree.

Table 7. Comparison of different groups in the Vickers hardness test.

Variables (Polished vs. Unpolished)	Mean	SD	CI		<i>p</i>
			Lower	Upper	
Milled	−0.24	2.21	−1.46	0.98	0.681
3D-printed (0°)	−3.15	0.25	−3.02	−3.02	0.0001 *
3D-printed (45°)	−4.81	0.25	−4.95	−4.67	0.0001 *
3D-printed (90°)	−5.02	0.53	−5.32	−4.72	0.0001 *

SD; standard deviation, CI; confidence interval, *p*; *p*-value, 3D; Three-dimension, vs.; versus, °; degree, *; statistically significant (*p* < 0.05).

5. Discussion

The current study assessed the mechanical properties, specifically the flexural strength test, compressive strength test, and Vickers hardness test of CAD/CAM fabricated hybrid ceramic restoration materials manufactured by subtractive and additive techniques. The hypothesis of this study has been rejected. The results of the present study showed that there were significant differences between subtractively and additively manufactured CAD/CAM fabricated hybrid ceramic restorative materials.

In the current study, a three-point bending flexure strength test was carried out for hybrid ceramic materials manufactured by additive and subtractive manufacturing techniques. The additive manufacturing technique showed significant differences among both the milled and the three different degrees (0°, 45°, and 90°) of 3D-printed groups in the flexural strength test. A similar test was also conducted in previous studies [36,37]; nevertheless, the groups being compared were selected differently. Sahin et al. [37] chose six composite resin materials for subtractive manufacturing and three composite resin

materials for additive machine manufacturing. Furthermore, Temizci et al. [36] included two subtractive composite-based blocks and two additive composite-based resins used for two different polymerization methods. The current study included only one type of hybrid ceramic restorative material for additive and subtractive techniques. Nevertheless, even though there were differences in material selection, all studies, including the current study, showed significant differences when compared to the flexure strength among groups. The subtractive technique showed more flexure strength than the additive technique in this outcome. Flexure strength is termed to be capable to withstand the combination of tensile and compressive stresses [24,38]. To determine the mechanical characteristics of hybrid ceramic restorative materials, flexure strength plays an imperative role [38]. In the current study, the flexure strength value of milled hybrid ceramic restorative material achieved the ISO specifications [34]. A similar outcome was also observed in a study by Sahin et al. [37]; however, the ISO standard was different from that of the current study.

The current study showed that there were significant differences among milled and three different degrees (0° , 45° , and 90°) of 3D-printed groups in the compressive strength test. However, unlike the flexure strength, the 3D printing group or additive manufacturing showed more compressive strength compared to the milled or subtractive material. Most of the previous studies, which were aimed at the mechanical properties of hybrid ceramic materials in additive and subtractive manufacturing, did not focus on compressive strength. Therefore, a direct comparison of the outcome of the current study was not possible. A prior study evaluated the compressive strength of temporary fixed dental prostheses and demonstrated that 3D-printed temporary resins outperformed conventional resins in terms of compressive strength [39].

The Vickers hardness test was performed using the polished and unpolished subtractive and additive manufacturing techniques. The outcome of the Vickers hardness test showed a significant difference in three different degrees (0° , 45° , and 90°) of 3D-printed groups between the polished and unpolished versions; however, no significant difference was observed between the polished and unpolished versions of the milled or subtractive manufacturing technique. The milled group showed the highest hardness mean value, followed by 3D-printed 90° , 45° , and 0° . Similar to compressive strength, according to the literature search, no previous study has compared the Vickers hardness test between polished and unpolished subtractive and additive manufacturing techniques. Hence, a direct comparison of the outcomes could not be established. However, previous studies assessed the Vickers hardness test in different hybrid ceramic materials with additive and subtractive manufacturing techniques [36,37]. Although the specific approach of the aforementioned reports differed from the present investigation, materials produced by subtractive manufacturing exhibited higher hardness than those produced by additive manufacturing, which aligns with the findings of the present study.

The materials prepared through milling techniques are far superior to the materials produced through 3D printing. Different angles of 3D printing do not significantly improve the quality of forces in different scenarios. It is hence proven through the results that the materials prepared through milling techniques are better suited to be used in clinical practice than the materials of 3D printing. The anterior teeth are not subjected to extreme forces in the oral cavity, so 3D-printed materials can be used in their restorations. In contrast, milled material is better suited to the posterior area due to its higher compressive and flexural strength.

The results of the hybrid ceramic material obtained from the study show that there is a significant difference in the strength values of the material to the commonly used materials in the market. These materials include zirconia, lithium disilicate porcelain, etc. The properties of the hybrid ceramic material are better than the porcelain concerning the compressive and flexural strength [40]. On the other hand, zirconia is a much better candidate than the restorative material used in the study with respect to the strength tests of the material [40]. Zirconia is, therefore, better suited for posterior restorations where strength is the main focus of the restoration [40]. Lithium disilicate is a better candidate

than the hybrid ceramic material, where aesthetics is the prime focus of the restoration [41]. They come in multiple shades and are closely related to the normal color of teeth for shade-matching [41]. The hybrid ceramic material is, therefore, comparable to all the commonly used materials in the market. The choice of the material is always subject to the preference of the patient, the location of the restoration, and the best property suited to the requirement of the restoration [41]. The load-to-failure ratio of different materials is calculated, and the material is selected according to the intended need. Further comparative analysis is required to reach a definitive conclusion in different prospects of properties of materials [40].

The values of compressive strength, flexural strength, and hardness levels of the material used in the study are in comparison with the normal dental enamel, so the material can be used effectively as a long-term alternative in dental procedures [42].

Moreover, printing orientation can have marked differences in strength values in the hybrid ceramic material. It has been subjectively proven in the literature that the most effective values of different strengths are obtained by printing the material at 0 degrees and gradually decreasing with an increase in the angle of printing. Multiple studies in the literature have also proven that the orientation of printing plays a crucial role in determining the strength of the material. Therefore, the preference should be to print the material at 0 degrees instead of other angles. In addition to the printing orientation, the post-curing time of the prepared material also determines its strength in different situations. The greater post-curing time is associated with higher strength values and far superior results as compared to less time [43].

The core strength values of the tested material are far superior to the provisional 3D-printed resin being used commonly in the dental practice of lower-income countries and have been discussed extensively in the literature. The material tested shows a significant difference in values in all aspects of the strengths, which is far better than that of conventional 3D resin. This material has the full-blown potential to be used as a long-term replacement for the orthodox resins being used [44]. A long-term and definitive restoration requires consideration of multiple factors that can play a significant role in the upcoming time for the patient. The requirements of the patient are the primary considerations, which can vary from strength, appearance, sensitivity, and other related issues. The choice of material and the process that is adopted to prepare the material is decided by keeping in view the financial affordability of the patient, availability of the material and facilities, the time required for the preparation, strength values, and many more. The best suitable decision varies from situation to situation [45].

This study possesses some limitations; only one type of hybrid ceramic material was used in this study. However, using different hybrid ceramic materials and comparing the different materials with 3D printing and subtractive techniques would have provided more insight to this study. Therefore, future studies considering different combinations would yield more comprehensive outcomes.

6. Conclusions

This study highlights significant variations in the mechanical properties of hybrid ceramic materials, emphasizing the impact of manufacturing techniques and printing orientations; within the limitation of the current study, the following could be concluded:

1. The subtractive group achieved ISO specifications in terms of flexural strength. This group was superior to additive groups in hardness while exhibiting lower performance in compressive strength;
2. Printing orientation had a significant influence on the performance of additive groups. Flexural strength and hardness were improved when the printing orientation was in alignment with the direction of load (90°), while compressive strength was improved when the printing orientation was perpendicular to the direction of load (0°);
3. Polishing did not significantly improve the hardness values of the subtractive group;

4. Additive groups' hardness values were significantly improved post-polishing, highlighting its importance for 3D-printed restorations.

7. Clinical Significance

Hybrid ceramic materials proved to be effective in either subtractive or 3D printing techniques, which enable general practitioners to use them in dental practice routinely. However, the materials prepared through milling techniques are far superior to the materials produced through 3D printing.

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References

1. Dawood, A.; Marti, B.M.; Sauret-Jackson, V.; Darwood, A. 3D printing in dentistry. *Bri. Dent. J.* **2015**, *219*, 521–529.
2. Abduo, J.; Lyons, K.; Bennamoun, M. Trends in computer-aided manufacturing in prosthodontics: A review of the available streams. *Int. J. Dent.* **2014**, *2014*, 783948. [[CrossRef](#)] [[PubMed](#)]
3. Moon, W.; Kim, S.; Lim, B.-S.; Park, Y.-S.; Kim, R.J.-Y.; Chung, S.H. Dimensional accuracy evaluation of temporary dental restorations with different 3D printing systems. *Materials* **2021**, *14*, 1487. [[CrossRef](#)]
4. Kantaros, A.; Ganetsos, T.; Piromalis, D. 3D and 4D printing as integrated manufacturing methods of industry 4.0. *Am. J. Appl. Sci.* **2023**, *16*, 12–22. [[CrossRef](#)]
5. Stawarczyk, B.; Liebermann, A.; Eichberger, M.; Güth, J.-F. Evaluation of mechanical and optical behavior of current esthetic dental restorative CAD/CAM composites. *J. Mech. Behav. Biomed. Mater.* **2016**, *55*, 1–11. [[CrossRef](#)] [[PubMed](#)]
6. Oouchi, H.; Takamizawa, T.; Tamura, T.; Ishii, R.; Tsujimoto, A.; Miyazaki, M.; Kitahara, N. Flexural properties and wear behavior of computer-aided design/computer-aided manufacturing resin blocks. *Dent. Mater. J.* **2021**, *40*, 979–985. [[CrossRef](#)]
7. Alharbi, A.; Ardu, S.; Bortolotto, T.; Krejci, I. Stain susceptibility of composite and ceramic CAD/CAM blocks versus direct resin composites with different resinous matrices. *Odontology* **2017**, *105*, 162–169. [[CrossRef](#)]
8. He, L.-H.; Purton, D.; Swain, M. A novel polymer infiltrated ceramic for dental simulation. *J. Mater. Sci. Mater. Med.* **2011**, *22*, 1639–1643. [[CrossRef](#)]
9. Zimmermann, M.; Mehl, A.; Reich, S. New CAD/CAM materials and blocks for chairside procedures. *Int. J. Comput. Dent.* **2013**, *16*, 173–181.
10. Kessler, A.; Reymus, M.; Hickel, R.; Kunzelmann, K.-H. Three-body wear of 3D printed temporary materials. *Dent. Mater.* **2019**, *35*, 1805–1812. [[CrossRef](#)]
11. Kihara, H.; Sugawara, S.; Yokota, J.; Takafuji, K.; Fukazawa, S.; Tamada, A.; Hatakeyama, W.; Kondo, H. Applications of three-dimensional printers in prosthetic dentistry. *J. Oral Sci.* **2021**, *63*, 212–216. [[CrossRef](#)] [[PubMed](#)]
12. Zimmermann, M.; Ender, A.; Egli, G.; Özcan, M.; Mehl, A. Fracture load of CAD/CAM-fabricated and 3D-printed composite crowns as a function of material thickness. *Clin. Oral Investig.* **2019**, *23*, 2777–2784. [[CrossRef](#)]
13. Zimmermann, M.; Ender, A.; Attin, T.; Mehl, A. Fracture load of three-unit full-contour fixed dental prostheses fabricated with subtractive and additive CAD/CAM technology. *Clin. Oral Investig.* **2020**, *24*, 1035–1042. [[CrossRef](#)]

14. Zimmermann, M.; Egli, G.; Zaruba, M.; Mehl, A. Influence of material thickness on fractural strength of CAD/CAM fabricated ceramic crowns. *Dent. Mater. J.* **2017**, *36*, 778–783. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Della Bona, A.; Cantelli, V.; Britto, V.T.; Collares, K.F.; Stansbury, J.W. 3D printing restorative materials using a stereolithographic technique: A systematic review. *Dent. Mater.* **2021**, *37*, 336–350. [\[CrossRef\]](#)
16. Dimitrov, D.; Schreve, K.; de Beer, N. Advances in three dimensional printing—state of the art and future perspectives. *Prototyp. J.* **2006**, *12*, 136–147. [\[CrossRef\]](#)
17. Alharbi, N.; Osman, R.; Wismeijer, D. Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations. *J. Prosthet. Dent.* **2016**, *115*, 760–767. [\[CrossRef\]](#)
18. Mueller, J.; Shea, K. The effect of build orientation on the mechanical properties in inkjet 3D printing. *UT. Austin* **2015**. Available online: <https://hdl.handle.net/2152/89394> (accessed on 29 July 2024).
19. Keßler, A.; Hickel, R.; Ilie, N. In vitro investigation of the influence of printing direction on the flexural strength, flexural modulus and fractographic analysis of 3D-printed temporary materials. *Dent. Mater. J.* **2021**, *40*, 641–649. [\[CrossRef\]](#)
20. Cazzaniga, G.; Ottobelli, M.; Ionescu, A.C.; Paolone, G.; Gherlone, E.; Ferracane, J.L.; Brambilla, E. In vitro biofilm formation on resin-based composites after different finishing and polishing procedures. *J. Dent.* **2017**, *67*, 43–52. [\[CrossRef\]](#)
21. Ruse, N.; Sadoun, M. Resin-composite blocks for dental CAD/CAM applications. *J. Dent. Res.* **2014**, *93*, 1232–1234. [\[CrossRef\]](#)
22. Block, P.M. *Technical Product Profile*; 3M ESPE: St. Paul, MN, USA, 2000.
23. Lava Ultimate, C. *CAM Restorative Technical Product Profile*; 3M ESPE: St. Paul, MN, USA, 2011.
24. Ling, L.; Ma, Y.; Malyala, R. A novel CAD/CAM resin composite block with high mechanical properties. *Dent. Mater.* **2021**, *37*, 1150–1155. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Della Bona, A.; Corazza, P.H.; Zhang, Y. Characterization of a polymer-infiltrated ceramic-network material. *Dent. Mater.* **2014**, *30*, 564–569. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Zahnfabrik, V. *VITA ENAMIC Technical and Scientific Documentation*; VITA Zahnfabrik: Bad Sackingen, Germany, 2019.
27. Kantaros, A.; Petrescu, F.I.T.; Abdoli, H.; Diegel, O.; Chan, S.; Iliescu, M.; Ganetsos, T.; Munteanu, I.S.; Ungureanu, L.M. Additive Manufacturing for Surgical Planning and Education: A Review. *Appl. Sci.* **2024**, *14*, 2550. [\[CrossRef\]](#)
28. Kantaros, A.; Soulis, E.; Ganetsos, T.; Petrescu, F.I.T. Applying a combination of cutting-edge industry 4.0 processes towards fabricating a customized component. *Processes* **2023**, *11*, 1385. [\[CrossRef\]](#)
29. Strub, J.R.; Rekow, E.D.; Witkowski, S. Computer-aided design and fabrication of dental restorations: Current systems and future possibilities. *J. Am. Dent. Assoc.* **2006**, *137*, 1289–1296. [\[CrossRef\]](#)
30. Salmi, M.; Paloheimo, K.-S.; Tuomi, J.; Ingman, T.; Mäkitie, A. A digital process for additive manufacturing of occlusal splints: A clinical pilot study. *J. R. Soc. Interface* **2013**, *10*, 20130203. [\[CrossRef\]](#)
31. Martorelli, M.; Gerbino, S.; Giudice, M.; Ausiello, P. A comparison between customized clear and removable orthodontic appliances manufactured using RP and CNC techniques. *Dent. Mater.* **2013**, *29*, e1–e10. [\[CrossRef\]](#)
32. Kantaros, A.; Ganetsos, T.; Petrescu, F.I.T. Transforming object design and creation: Biomaterials and contemporary manufacturing leading the way. *Biomimetics* **2024**, *9*, 48. [\[CrossRef\]](#)
33. Chaysuwan, D.; Sirinukunwattana, K.; Kanchanatawewat, K.; Heness, G.; Yamashita, K. Machinable glass-ceramics forming as a restorative dental material. *Dent. Mater. J.* **2011**, *30*, 358–367. [\[CrossRef\]](#)
34. ISO 4049; Dentistry—Polymer—Based Restorative Materials. International Organization for Standardization: Geneva Switzerland, 2009.
35. ADA Council on Scientific Affairs. *American National Standard/American Dental Association Specification No. 32 for Orthodontic Wires*; ADA Council on Scientific Affairs: Chicago, IL, USA, 2000.
36. Temizci, T.; Bozoğulları, H.N. Effect of thermocycling on the mechanical properties of permanent composite-based CAD-CAM restorative materials produced by additive and subtractive manufacturing techniques. *BMC Oral Health* **2024**, *24*, 334. [\[CrossRef\]](#)
37. Sahin, Z.; Ozer, N.; Kılıçarslan, M. Mechanical characteristics of composite resins produced by additive and subtractive manufacturing. *Eur. J. Prosthodont. Restor. Dent.* **2023**, *31*, 278–285.
38. Prpić, V.; Schauperl, Z.; Ćatić, A.; Dulčić, N.; Čimić, S. Comparison of mechanical properties of 3D-printed, CAD/CAM, and conventional denture base materials. *J. Prosthodont.* **2020**, *29*, 524–528. [\[CrossRef\]](#)
39. Pantea, M.; Ciocoiu, R.C.; Greabu, M.; Ripszky Totan, A.; Imre, M.; Țăncu, A.M.C.; Sfeatu, R.; Spînu, T.C.; Ilinca, R.; Petre, A.E. Compressive and flexural strength of 3D-printed and conventional resins designated for interim fixed dental prostheses: An in vitro comparison. *Materials* **2022**, *15*, 3075. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Gonzalez-Bonilla, M.; Berrendero, S.; Moron-Conejo, B.; Martinez-Rus, F.; Salido, M.P. Clinical evaluation of posterior zirconia-based and porcelain-fused-to-metal crowns with a vertical preparation technique: An up to 5-year retrospective cohort study. *J. Dent.* **2024**, *28*, 104953. [\[CrossRef\]](#)
41. Abrisham, S.M.; Tafti, A.F.; Kheirkhah, S.; Tavakkoli, M.A. Shear bond strength of porcelain to a base-metal compared to zirconia core. *J. Dent. Biomater.* **2017**, *4*, 367.
42. Chun, K.J.; Choi, H.H.; Lee, J.Y. Comparison of mechanical property and role between enamel and dentin in the human teeth. *J. Dent. Biomech.* **2014**, *5*, 1758736014520809. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Farkas, A.Z.; Galatanu, S.V.; Nagib, R. The influence of printing layer thickness and orientation on the mechanical properties of DLP 3D-printed dental resin. *Polymers* **2023**, *15*, 1113. [\[CrossRef\]](#) [\[PubMed\]](#)

44. Amend, S.; Seremidi, K.; Kloukos, D.; Bekes, K.; Frankenberger, R.; Gizani, S.; Kraemer, N. Clinical effectiveness of restorative materials for the restoration of carious primary teeth: An umbrella review. *J Clin. Med.* **2022**, *11*, 3490. [[CrossRef](#)]
45. Robaian, A.; Alotaibi, N.M.; Allaboon, A.K.; AlTuwaijri, D.S.; Aljarallah, A.F.; Alshehri, R.S.; Alabsi, A.A.; Mirza, M.B.; Al Moaleem, M.M. Factors Influencing Dentists' Choice of Restorative Materials for Single-Tooth Crowns: A Survey Among Saudi Practitioners. *Med. Sci. Monit. Int. Med. J. Exp. Clin. Res.* **2024**, *30*, e942723-1. [[CrossRef](#)]

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