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Original article

COMPARATIVE EVALUATION OF THE MECHANICAL PROPERTIES OF 3D-PRINTED DENTURE BASE RESINS

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ABSTRACT

Purpose: This in vitro study evaluated the flexural strength and hardness of several commercially available 3D-printed denture base resins in comparison with conventional heat-polymerized polymethyl methacrylate (PMMA).

Materials/Methods: A total of 80 specimens were fabricated for flexural strength and hardness testing. Four denture base materials were investigated: one conventional heat-polymerized PMMA resin (Superacryl Plus, Spofa Dental) and three stereolithography (SLA)-based 3D-printed resins (Denture Base Resin, Formlabs; Denture 3D+, NextDent; and Optiprint, Dentona). For each material, ten specimens were subjected to three-point bending tests, and ten were evaluated for Vickers hardness. All printed specimens were fabricated at a 0° build orientation and subjected to standardized post-processing procedures.

Results: Statistically significant differences were observed among the tested materials for both flexural strength and hardness ($p < 0.001$). NextDent exhibited the highest flexural strength values (166.61 ± 19.08 MPa), whereas Dentona demonstrated the lowest values (78.04 ± 17.01 MPa). Regarding hardness, Dentona exhibited the highest Vickers hardness values (27.4 ± 0.82), while Formlabs demonstrated the lowest hardness values (14.15 ± 1.42).

Conclusions: Within the limitations of this study, all tested 3D-printed denture base materials fulfilled the minimum ISO requirements for flexural strength. Certain printable resins demonstrated mechanical properties comparable to or superior to conventional heat-polymerized PMMA, indicating the growing potential of additive manufacturing technologies in removable prosthodontics.

Keywords: 3D printing, CAD/CAM, flexural strength, hardness, dentures,

INTRODUCTION

In recent years, there has been a notable shift in prosthodontics toward the use of digital technologies for the fabrication of removable dentures. Among these technologies, additive manufacturing has emerged as a promising method due to its accuracy, efficiency, reduced material waste, and flexibility in design customization [1, 2].

Mechanical properties are of paramount importance when selecting materials for denture fabrication. During mastication, denture bases are subjected to complex loading conditions, including compression, tension, bending, and shear forces. To resist deformation and fracture during function, denture base materials must demonstrate adequate mechanical strength and durability [3].

Flexural strength is considered one of the most important mechanical properties of denture base materials because it reflects their ability to resist deformation and fracture under functional loading. Insufficient flexural strength may increase the risk of crack formation and midline fractures, which are among the most common clinical complications associated with removable dentures. Additionally, denture bases are continuously subjected to cyclic loading in the oral environment, making adequate resistance to fatigue and bending stresses essential for long-term clinical success [4].

Hardness is another important property of denture base materials because it is closely related to wear resistance and the maintenance of surface integrity over time. Materials with insufficient hardness may become more susceptible to abrasion during mastication and denture hygiene procedures, potentially compromising their long-term durability and clinical performance [5].

Following the introduction of additive manufacturing technologies in dental medicine, numerous studies

have evaluated the properties of 3D-printed denture base resins in comparison with conventional heat-polymerized polymethyl methacrylate (PMMA) [6, 7, 8, 9]. Several investigations have reported that 3D-printed resins exhibit lower mechanical performance, particularly regarding flexural strength and hardness, compared with conventional heat-cured materials. Studies by Freitas RFCP, et al. [7] Al-Qarni FD, et al. [10], Chhabra M, et al. [11] demonstrated that heat-polymerized resins possess superior flexural strength and durability, whereas 3D-printed materials show greater plastic deformation and lower resistance to fracture. Falahchai M, et al. [12] reported that heat-polymerized resins exhibited higher flexural strength, modulus of elasticity, and hardness values, while 3D-printed materials demonstrated improved impact strength. In contrast, Altarazi A, et al. [13] suggested that recent developments in additive manufacturing have led to significant improvements in the mechanical and physical properties of 3D-printing polymers, indicating their potential as alternatives to conventional denture fabrication techniques.

Recent evidence suggests that modifications in the composition of 3D-printed denture base resins may significantly influence their mechanical behavior [14, 15]. A recent systematic review and meta-analysis reported that resin-modified printable materials demonstrated improvements in several mechanical properties, including impact strength, fracture toughness, elastic modulus, and microhardness, although flexural strength values were significantly reduced in some formulations. These findings indicate that optimization of printable denture base resins may involve a complex balance between different mechanical characteristics [16].

Despite the increasing number of studies evaluating additively manufactured denture base resins, the reported results remain inconsistent. Differences in printing technologies, resin composition, layer thickness, build orientation, and post-curing protocols may significantly influence the mechanical properties of the final printed structures [17]. Consequently, further investigations are necessary to better understand the mechanical behavior of commercially available 3D-printed denture base materials.

Therefore, the aim of the present in vitro study was to evaluate and compare the flexural strength and hardness of several 3D-printed denture base resins with those of conventional heat-polymerized PMMA.

MATERIALS AND METHODS

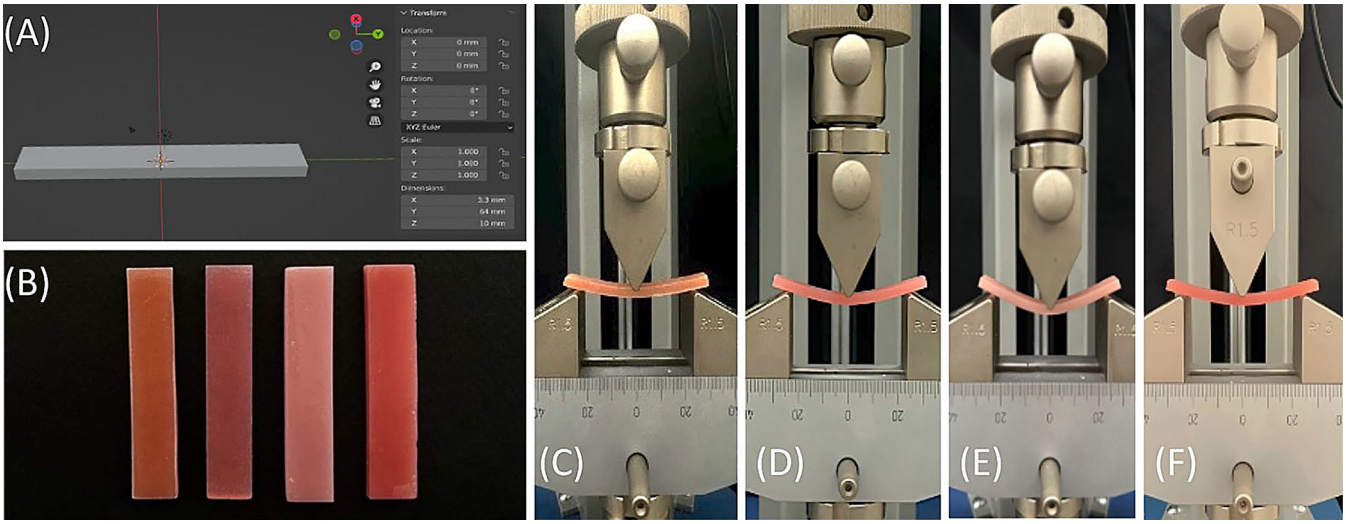
A total of 80 specimens were fabricated for the evaluation of flexural strength and hardness. Four denture base materials were investigated, with 20 specimens prepared for each material (n = 20). For each material, 10 specimens were allocated to flexural strength testing (n = 10), and 10 specimens were allocated to Vickers hardness testing (n = 10). The specimens were divided into four groups according to the tested material:

- Group A – heat-polymerized resin Superacryl Plus (Spofa Dental, Jicin, Czech Republic)
- Group B – 3D-printed Denture Base Resin (Formlabs, MA, USA)
- Group C – 3D-printed Denture 3D+ (NextDent, 3D Systems, Soesterberg, Netherlands)
- Group D – 3D-printed Optiprint (Dentona, Germany)

For the fabrication of the heat-polymerized specimens, a silicone mold was used following the conventional compression molding technique. After flasking, the resin was packed into the mold during the dough stage, pressed, and subjected to thermal polymerization. The polymerization cycle consisted of immersion at room temperature, followed by processing at 70°C for 90 minutes and subsequently at 100°C for 30 minutes. After polymerization, the specimens were deflasked and finished using a tungsten carbide bur to remove excess resin. All specimens were measured at three different points using an electronic caliper to verify dimensional accuracy. Following fabrication and post-processing, all specimens were immersed in distilled water at room temperature for 48 hours prior to mechanical testing.

The 3D-printed specimens were designed using CAD software (Blender v. 3.5) (fig. 1A, fig. 2A) and exported as Standard Tessellation Language (STL) files. The STL files were processed using the corresponding printing software and fabricated at a 0° build orientation using stereolithography (SLA)-based 3D-printing systems (Group B – Form 2, Formlabs; Group C – Pro S, NextDent; Group D – Ackuretta).

Fig. 1. A) Digital Design of the 3D printed specimens according to ISO 20795-1:2013; **B)** Specimens from Group A, B, C and D; **C)** Specimen from Group A during the flexural strength test; **D)** Specimen from Group B during the flexural strength test; **E)** Specimen from Group C during the flexural strength test; **F)** Specimen from Group D during the flexural strength test;



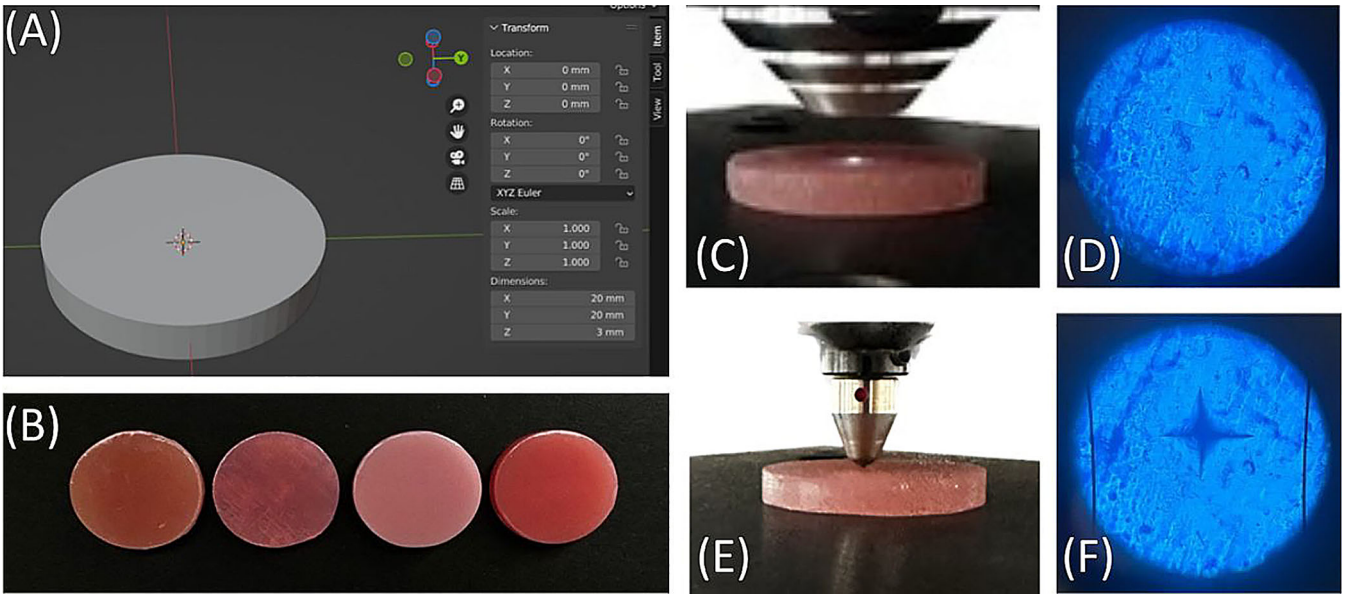
Post-processing of the printed specimens included washing in 95% isopropyl alcohol using an ultrasonic cleaning system (Group B – Form Wash, Formlabs; Group C – Pro Wash, NextDent; Group D – CLEANI, Ackuretta), followed by post-curing in a photopolymerization unit (Group B – Form Cure, Formlabs; Group C – Pro Cure, NextDent; Group D – Ackuretta UV Box) for 30 minutes at 80°C using ultraviolet light with a wavelength of 405 nm. After post-processing, all specimens were stored in distilled water at room temperature until mechanical testing was performed.

For flexural strength testing, 40 rectangular specimens were fabricated according to ISO 20795-1:2013 specifications with dimensions of 64 × 10 × 3 ± 0.2 mm (fig. 1B). For hardness testing, 40 disc-shaped specimens were fabricated according to ISO 6507-1:2018 with dimensions of 20 × 3 ± 0.2 mm (fig. 2B).

The three-point bending test was used to evaluate flexural strength (Figure 1C–F). Testing was performed using a MultiTest 2.5-i system (Mecmesin Ltd., UK), which measures the load required to deform and fracture the specimens under non-axial opposing forces. The maximum applicable force was 1000 N. Flexural strength (FS) was automatically calculated using the Emperor™ software according to the following formula: $FS = 3(F)(L)/2bh^{2,}$ where F represents the applied force, L the distance between the support points, b the width of the specimen, and h the specimen thickness.

Hardness measurements were performed using a Zwick Roell ZHVμ microhardness tester (Indentec Hardness Testing Machines Ltd., UK). The Vickers indenter had a diamond pyramidal geometry with a square base and an angle of 136°. Each specimen was initially focused (fig. 2C, D) and subsequently subjected to a load of 0.5 kg for 10 seconds (fig. 2E, F). Four measurements were performed on each specimen (n = 10 per experimental group). The Vickers Hardness Number (VHN) was automatically calculated by the testing system software for each indentation. The mean of the four measurements was calculated to obtain a representative hardness value for each specimen. These specimen-level mean values were subsequently used for the statistical analysis.

Fig. 2. A) Digital design of the 3D printed specimens; **B)** Specimens from Groups A, B, C and D; **C)** The specimen is set in focus; **D)** Microscopy image of the specimen before the test; **E)** Indentation; **F)** Microscopy image of the specimen after the test;



Statistical analysis was performed using SPSS Statistics version 26 (IBM, USA). Data distribution was evaluated prior to analysis. One-way ANOVA followed by Tukey's post hoc test was used for pairwise comparisons between groups. A p-value < 0.05 was considered statistically significant.

RESULTS

The mean values, standard deviations, and results of the one-way analysis of variance (ANOVA) for flexural strength and Vickers Hardness Number (VHN) are presented in Table 1.

Table 1. Mean values, standard deviations, and statistical comparisons of flexural strength and Vickers hardness among the investigated denture base materials.

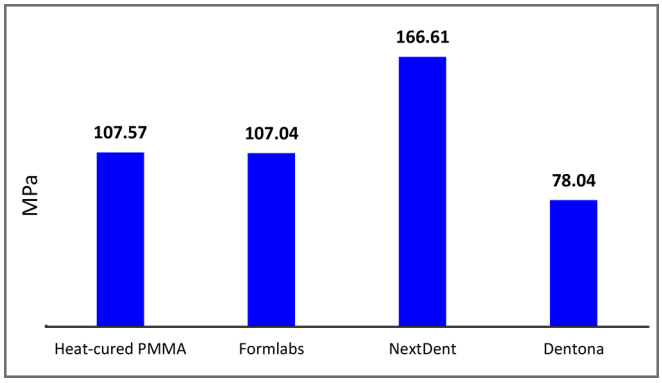
Material (Group)		**Flexural strength (MPa)**	**VHN**
		Mean ± SD	
Heat-cured PMMA (A)		107.57 ± 12.27[a]	17.55 ± 2.48[a]
Formlabs (B)		107.04 ± 19.68[a]	14.15 ± 1.42[b]
NextDent (C)		166.61 ± 19.08[b]	16.85 ± 4.49[ab]
Dentona (D)		78.04 ± 17.01[c]	27.40 ± 0.82[c]
One-way ANOVA	**F-value**	46.44	46.38
	P-value	<0.001	<0.001

Note: Within each column, groups sharing at least one superscript letter are not significantly different, whereas groups with no letters in common differ significantly according to Tukey's HSD post hoc test (p < 0.05).

Statistically significant differences were observed among the tested materials for both flexural strength and hardness (p < 0.001).

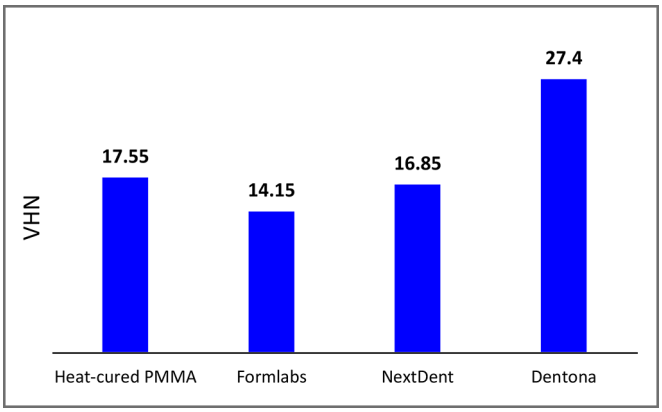
Regarding flexural strength, the NextDent 3D-printed resin demonstrated the highest mean value (166.61 MPa), followed by the heat-cured PMMA resin (107.57 MPa) and the Formlabs material (107.04 MPa), whereas the Dentona material exhibited the lowest flexural strength value (78.04 MPa) (fig. 3). All tested materials exceeded the minimum flexural strength requirement of 65 MPa specified by ISO 20795-1:2013 for denture base polymers. Group C (NextDent) demonstrated significantly higher flexural strength than the other tested materials. Group B (Formlabs) showed values comparable to those of Group A (heat-cured PMMA), with no statistically significant difference observed between these groups, whereas Group D (Dentona) demonstrated the lowest flexural strength values.

Fig. 3. Comparison of mean flexural strength values (MPa) among the four investigated denture base materials: conventional heat-cured PMMA, Formlabs, NextDent, and Dentona.



For hardness measurements, Group D (Dentona) demonstrated the highest Vickers Hardness Number values and differed significantly from the other groups ($p < 0.001$) (fig. 4). No statistically significant difference in hardness was observed between Group A (heat-cured PMMA) and Group C (NextDent). Group B (Formlabs) showed the lowest hardness values.

Fig. 4. Comparison of mean Vickers hardness values (VHN) among the four investigated denture base materials: conventional heat-cured PMMA, Formlabs, NextDent, and Dentona.



DISCUSSION

The findings of the present study revealed significant differences in flexural strength and hardness among the investigated denture base materials, highlighting the potential influence of material composition and manufacturing technology on their mechanical behavior. These differences suggest that the mechanical performance of 3D-printed denture base resins is material-dependent and may vary considerably between commercially available products.

The superior flexural strength observed in the NextDent group may be attributed to differences in resin composition, degree of polymer conversion, printing parameters, and post-processing protocols. Variations in photopolymer formulations and cross-linking density among manufacturers may influence the final mechanical properties of printed materials. Conversely, the lower flexural strength observed in the Dentona group may be associated with differences in its polymer composition or polymerization characteristics. However, these potential explanations should be interpreted cautiously, as the degree of conversion and polymer network structure were not directly evaluated in the present study.

The findings of the present study partially agree with previous investigations evaluating the mechanical properties of 3D-printed denture base materials. Similarly, Di Fiore A, et al. [18] reported that CAD/CAM milled PMMA demonstrated superior flexural properties compared with both conventional and 3D-printed denture base materials. Their findings further support the influence of fabrication technique on the mechanical behavior of denture base resins and suggest that additively manufactured materials may still exhibit lower resistance to functional loading compared with subtractive manufacturing approaches. However, unlike their findings, the NextDent material evaluated in the present study demonstrated flexural strength values exceeding those of the conventional heat-polymerized resin. Fouda SM, et al. [19] reported no significant difference between the NextDent and Formlabs groups, whereas the present study demonstrated significantly higher flexural strength values for the NextDent material. Similarly, Altarazi A, et al. [13] suggested that recent developments in additive manufacturing technologies have improved the mechanical properties of printable denture base resins, supporting the promising results observed in the present investigation.

An interesting finding of the present study was the contrasting mechanical behavior of the Dentona material, which exhibited the highest surface hardness but the lowest flexural strength among the investigated materials. This observation suggests that hardness and flexural strength represent distinct mechanical characteristics and do not necessarily correlate directly. While higher hardness indicates greater resistance to localized indentation, lower flexural strength reflects reduced resistance to bending stresses under the tested conditions. Similar observations have been reported in investigations evaluating modified 3D-printed denture base formulations. Hetzler et al. [20] demonstrated that improvements in fracture-related properties of modified printable resins were accompanied by reductions in hardness values, suggesting that optimization of one mechanical property may adversely affect another. These findings emphasize that hardness, fracture resistance, and flexural behavior should be considered complementary rather than interchangeable indicators of material performance.

Variations in manufacturing technologies and experimental protocols may contribute to the discrepancies in the mechanical properties of 3D-printed denture base resins reported across different studies. Di Fiore et al. [18] compared conventional heat-polymerized, CAD/CAM milled, and 3D-printed PMMA resins using six specimens per group for three-point bending tests, whereas the present investigation included ten specimens per material and employed slightly different specimen dimensions. Fouda et al. [19] evaluated a wider range of denture base materials, including both milled and 3D-printed resins, which may partly explain the differences in the reported mechanical performance. In addition, Altarazi et al. [13] reported favorable mechanical properties for specimens fabricated at a 90° printing orientation, whereas all specimens in the present study were printed at 0°. Beyond these methodological differences, variations in resin composition, layer thickness, interlayer adhesion, and post-curing conditions may further influence the mechanical behavior of additively manufactured materials. Therefore, comparisons between studies should take into account differences in material selection, manufacturing parameters, and testing protocols to ensure an appropriate interpretation of the findings.

The hardness results obtained for the heat-polymerized resin and the NextDent material are comparable to those reported by Al-Dwairi ZN, et al. [21], who observed similar VHN values for both materials. In contrast, Gad MM, et al. [22] reported substantially higher hardness values for heat-polymerized PMMA and the NextDent material than those observed in the present study. Such discrepancies may be attributed to differences in specimen preparation, testing methodology, post-curing procedures, or material composition.

Printing orientation is an important factor that may significantly influence the mechanical behavior of additively manufactured denture base resins. The orientation of printed layers relative to the direction of the applied load may affect stress distribution and crack propagation, particularly at the interfaces between successive layers. Consequently, differences in interlayer adhesion and layer alignment may contribute to variations in flexural strength. In our previous study evaluating the influence of printing orientation on the mechanical properties of SLA-printed denture base resin, horizontally printed specimens (0° orientation) demonstrated the highest flexural strength values, whereas vertically printed specimens (90° orientation) exhibited lower resistance to bending stresses [23]. These findings suggest that differences in interlayer bonding and stress distribution may influence the mechanical performance of printed materials. Since all specimens in the present study were fabricated at a 0° build orientation, this orientation may have contributed to the relatively high flexural strength values observed in some of the tested materials, particularly the NextDent group. However, differences in flexural strength among materials printed at the same orientation may also reflect variations in resin composition, printing technology, and post-curing protocols. Therefore, build orientation should be considered an important parameter when evaluating and comparing the mechanical behavior of additively manufactured denture base resins.

LIMITATIONS

The present study has several limitations. First, as an in vitro investigation, it cannot fully reproduce the complex biological and functional conditions of the oral environment. Long-term aging procedures, such as thermocycling and water sorption, as well as cyclic fatigue loading, were not performed, although these factors may significantly influence the mechanical behavior and durability of denture base materials over time. Although all tested 3D-printed denture base materials exceeded the minimum flexural strength requirement specified by ISO 20795-1:2013, compliance with this standard alone does not guarantee their long-term clinical performance. Therefore, further investigations incorporating cyclic fatigue loading, artificial aging, thermocycling, and long-term water storage are necessary to assess their durability under simulated intraoral conditions.

Another limitation is that all specimens were fabricated using a single build orientation (0°). Since printing orientation may significantly affect interlayer adhesion, polymerization behavior, and crack propagation, the obtained results cannot be generalized to other printing configurations. Furthermore, only one post-curing protocol was applied for all tested materials. Variations in post-curing duration, temperature, and light intensity may influence the degree of polymer conversion and consequently alter the mechanical properties of printed resins.

The present study also evaluated a limited number of commercially available denture base materials; therefore, the findings may not be representative of all currently available additive manufacturing systems and resin formulations. In addition, the degree of monomer conversion and residual monomer content were not assessed, although these factors may affect the long-term stability and mechanical performance of the materials. Finally, microscopic or fractographic analysis of the fractured specimens was not performed, which could have provided additional information regarding crack propagation patterns and interlayer bonding behavior.

CONCLUSIONS

Within the limitations of the present in vitro study, all tested 3D-printed denture base materials fulfilled the minimum ISO requirements for flexural strength. Certain 3D-printed resins demonstrated mechanical properties comparable or superior to those of conventional heat-po-

lymerized PMMA.

Among the tested materials, Denture 3D+ (NextDent) demonstrated the highest flexural strength values, whereas Optiprint (Dentona) exhibited the highest Vickers hardness values. The results suggest that the mechanical behavior of 3D-printed denture base materials may vary considerably depending on the material composition and manufacturing system used.

The findings of the present study support the growing potential of additive manufacturing technologies for the fabrication of removable denture bases in contemporary prosthodontics.

ABBREVIATIONS:

3D – Three-Dimensional

CAD/CAM – Computer-Aided Design/Computer-Aided Manufacturing

FS – Flexural Strength

ISO – International Organization for Standardization

PMMA – Polymethyl Methacrylate

SD – Standard Deviation

SLA – Stereolithography

STL – Standard Tessellation Language

VHN – Vickers Hardness Number

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