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Flexural strength, fracture toughness, translucency, stain resistance, and water sorption of 3D-printed, milled, and conventional denture base materials

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Abstract

Purpose: To compare mechanical, optical, and physical properties of denture base materials fabricated with various 3D printing systems to reference milled and conventionally heat-processed denture base materials.

Materials and Methods: Specimens of denture base materials were either 3D-printed (DLP in-office printer, CLIP laboratory printer, or material jetting laboratory printer), milled, or heat processed. 3-point bend flexural strength testing was performed after 50 hours of water storage following 1hour of drying (dry testing) or in 37°C water (wet testing). Fracture toughness was performed with a notched beam specimen after 7 days of water storage and tested dry. The translucency parameter was measured with 2 mm thick specimens. Stain resistance was measured as color change following 14 days of storage in 37°C coffee. Water sorption was measured following 7 days of storage in 37°C distilled water.

Results: For dry testing, all but one of the 3D-printed materials attained higher or equivalent flexural strength as the reference materials. For wet testing, all 3D-printed materials attained higher or equivalent strength as the reference materials and dry-tested materials. For 3D-printed materials, wet testing increased displacement before fracture whereas it decreased displacement for the reference materials. Only two of the 3D-printed materials had similar fracture toughness as the reference materials. One of the 3D-printed materials was more translucent and one was more opaque than the reference materials. Only one of the 3D-printed materials absorbed more water than the reference materials.

Conclusion: 3D-printed denture base materials have mostly equivalent mechanical, optical, and physical properties to conventional and milled denture base materials.

KEYWORDS
denture, mechanical properties, removable prosthodontics

The materials used for 3D-printed dentures vary in composition from those used for milled and conventional heat-processed dentures which may affect their physical and mechanical properties. Most previous studies have reported that the flexural strength of 3D-printed denture base materials is lower than that of milled and conventional heat-processed denture base materials,[1–13] whereas some studies have reported an equivalent flexural strength for 3D-printed denture base materials and conventional heat-processed denture base materials.[13–14]

The mechanical behavior of dental materials is often described by the features of their stress(strength)-displacement plot from a bend test. The flexural strength reported is typically the maximum strength of the material achieved in the bend test. The area under the total curve represents toughness or the total energy absorbed before

fracture. For polymers, such as denture base materials, the polymer chains may slide past one another or unravel which leads to a decreased resistance to bending. However, the polymer chains may not break in a fracture of the material.[15] This characteristic of some polymers allows them to possess relatively high toughness despite having relatively low flexural strength. In other words, the polymer-based material will tend to bend rather than fracture. Therefore, flexural strength should not be the only property used to characterize denture base materials.

Several previous studies have reported a higher impact strength for 3D-printed denture base materials than conventional denture base materials,[3,4] although other studies reported lower impact strength of 3D-printed denture base materials than milled materials.[5–7] Mann et al. reported a higher fracture toughness of 3D-printed denture base than milled or conventional denture base,[16] whereas Abdul-Monem et al. reported a lower fracture toughness of a 3D-printed denture base than a milled denture base.[17] Several studies have indicated that 3D-printed denture materials undergo more displacement before failure than conventional or milled materials.[4,12]

The conditions under which denture base materials are tested affects their mechanical properties. The International Standards Organization (ISO) recommends testing the flexural strength of dentures in a 37°C water bath.[18] This testing condition represents the state of the denture base when immersed in saliva in a patients mouth. Most previous studies have examined the flexural strength of denture base materials either dry or immediately after being removed from water storage. The flexural strength of denture base materials decreases from dry storage and testing to wet storage and dry testing to wet storage and testing.[19] Testing in air has a tendency to increase flexural strength but lead to a more brittle failure.[20] In a study in which flexural strength was tested in 37°C water, several 3D-printed denture base materials had higher flexural strength than reference milled and conventional denture base materials.[21]

There is some concern that the photosensitive nature of the 3D-printed resins and their reduced viscosity which is required for additive manufacturing would create an overly translucent material. Although some translucency in a denture base may help to blend with surrounding tissue in some cases, an overly translucent denture base may have unwanted show-through of components such as attachments, locator housings, frameworks, or embedded portions of bonded denture teeth or fail to mask undesired tissues. One previous study reported higher translucency for 3D-printed denture bases than milled and conventional denture bases,[22] however, another reported less translucency.[23] Another concern is that 3D-printed denture materials absorb more water than milled or conventional denture base materials and will undergo increased staining. Some previous studies have reported more water sorption of 3D-printed materials than conventional and milled materials.[17,23] Also, several studies have reported increased staining of 3D-printed denture base materials.[3,24,25]

Of the 7 ISO categories of ASTM/ISO additive manufacturing technologies, the two commonly used in the fabrication of denture bases are vat photopolymerization and material jetting. Most previous studies have examined dentures 3D-printed in liquid-crystal display (LCD), stereolithography (SLA), or digital light processing (DLP) vat photopolymerization printers. Continuous liquid interface production (CLIP) has been adopted in dental laboratories as it is a type of vat printing that allows continuous printing through a liquid "dead zone" rather than layer-by-layer printing. Another form of printing adopted in laboratories is material jetting printing which offers the advantage of printing different resins within the same part (i.e. printing different resins for denture base and teeth). The resin materials themselves also affect their mechanical properties based on the resin composition or the presence of fillers.[26]

This study examined 3D-printed denture base materials fabricated in an in-office DLP printer as well as those used in laboratory CLIP and material jetting printers. The objective was to compare the flexural strength, fracture toughness, translucency, stain resistance, and water sorption of 3D-printed denture base materials to milled and conventional heat-processed material. Additionally, the flexural strength of the materials was tested under dry and wet conditions. The first null hypothesis was that there would be no differences in the properties of 3D-printed denture base materials and milled and conventional denture materials. The second null hypothesis was that there would be no difference in flexural strength of denture base materials tested dry and wet.

MATERIALS AND METHODS

Flexural strength testing

Flexural strength bars (65 × 10 × 3.3 mm) were designed according to ISO standard 20795-1:2013 (8.5). Denture Base II (Dentca, Torrance CA) and High Impact Denture Base (SprintRay, Los Angeles, CA) bars were fabricated using a DLP printer (Pro 55S, SprintRay). Specimens were arranged with the 65 × 10 mm face directly on the build plate (no supports, 100 μm layer thickness), washed in 91% isopropyl alcohol, air dried, and post-cured (Denture Base II in glycerin) in a light cure unit (ProCure 2, SprintRay) for 25 minutes (High Impact Denture Base) or 7 minutes (Denture Base II). Lucitone Digital Print (Dentsply Sirona, Charlotte, NC) bars (n = 20) were fabricated using a CLIP printer (M3 printer, Carbon, Redwood City, CA). Specimens were arranged with the 65 × 10 mm face directly on the build plate (no supports, 100 μm layer thickness), washed twice in an ultrasonic cleaner with 99% isopropyl alcohol, air dried, and post-cured in a light cure unit (DS Digital Cure, Dentsply Sirona) for 1 hour at 80° C preceded by a 30-min ramp-up phase to that temperature. TrueDent Resin (Stratasys, Rehovot, Israel) bars were fabricated using a material jetting printer (J5 DentaJet printer, Stratasys). Specimens were arranged with the 65 × 10 mm face towards the build plate

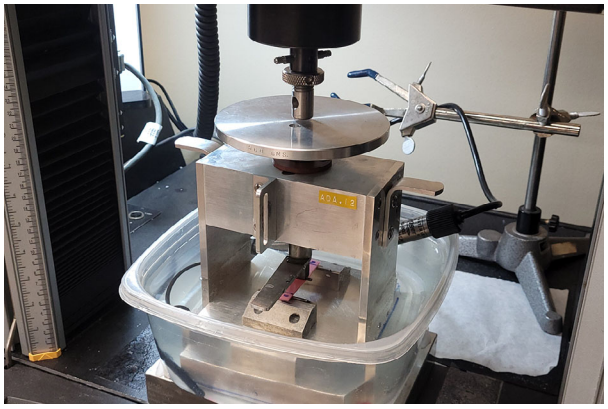

FIGURE 1 Flexural strength testing performed in 37°C water.

(supports, 11 μm layer thickness), washed using a water jet stream, soaked in 2% sodium hydroxide for 30 minutes, rinsed again with a water jet stream, and post-cured in glycerine in a light cure unit (TrueDent Cure, Stratasys) for 1 hour at 80°C. Bars were milled from Ivotion Base Milled Denture Base disc (Ivoclar Vivadent, Schaan, Liechtenstein) using a 5-axis dry mill (DWX-51D, Roland DG, Hamamatsu, Japan).

For the conventional heat-polymerized specimens, a block was 3D-printed and invested into a denture flask. Lucitone 199 Denture Base Resin (Dentsply Sirona) was mixed, allowed to reach packing consistency, packed into the denture flask, and placed under pressure using a hydraulic press machine (Chemetron, Coe Lab, Chicago, IL) for 10 minutes (maximum pressure 3,000 psi). The flask was placed in a heat curing unit (Model 4900, Nevin Labs, Chicago, IL) at 73°C for 90 minutes, followed by 30 minutes at a boiling temperature, and cooled. The acrylic block was then sectioned into individual bar specimens using a circular saw.

All specimens were wet polished to 600 grit SiC paper. The dimension of each specimen was verified after polishing with a digital caliper to be within the allowed margin of error of 0.2 mm. Specimens were pre-conditioned in 37°C water for 50 ±2 hours before testing.

The three-point bend test was performed for both dry and wet conditions. A sample size of 10/group was chosen based on the recommendations of ISO standard 20795-1:2013 (8.6) and the low standard deviation achieved with this property in previous testing. For dry testing (n = 10/group), the specimens were removed from water and allowed to sit at room temperature for 1 hour prior to testing. For wet testing (n = 10/group), the testing fixture was immersed in a water container maintained at a temperature of 37°C during testing. The specimens were placed onto a fixture in a universal testing machine (Instron 5565, Canton, MA) on 3 mm diameter supports separated by a 50 mm distance. A 2 mm diameter indenter applied force at the center of the bar at a vertical displacement rate of 5 mm/min until fracture (Figure 1). The test was stopped following 20 mm of vertical displacement of the indenter if the specimen did not break. The maximum failure load, along with the dimensions of the specimens, were used to calculate the flexural strength.

Fracture toughness testing

Fracture toughness bars (n = 10/group) were prepared following the same process described for flexural strength bar preparation using the dimensions specified in ISO standard 20795-1:2013 (8.6) (40 × 8 × 4 ±0.2 mm). To produce the pre-crack, a rotating circular saw blade (0.27 mm thickness, 6924.104.400, Komet, Rock Hill, SC) was used on a custom table saw to place a 3 ±0.2 mm cut in the center of the 40 × 4 mm face. A 100–400 μm notch was made in the center of the cut with a razor blade. The notch was produced with back-and-forth hand pressure under glycerol lubrication. The length of the notch was measured with a digital microscope (Keyence VHX, Tokyo, Japan). Specimens were stored in water at 37°C for 7 days and conditioned in 23°C water for 1 hour before testing. Each specimen was dried with a paper towel and placed in a universal testing machine (Instron 5565) with the pre-crack towards the bottom on 3 mm diameter supports separated by 32 mm. A 2 mm diameter indenter applied force at the top of the bar at a crosshead speed of 1 mm/min until fracture. The maximum failure load, crack length, and dimensions of the specimens were used to calculate fracture toughness.

Translucency and stain resistance

Disc specimens (15 mm diameter × 2 mm thickness) were prepared following the same process described for flexural strength bar preparation. Specimens were stored in 37°C water for 24 hours before testing. L*a*b* values were taken using a spectrophotometer (CM-700d; Konica Minolta, Ramsey, NJ) against white and black calibrated tiles. The color change was measured by ΔE2000 from the difference between the white and black background to determine the Translucency Parameter.

The same specimens were then stored in coffee for 14 days at a temperature of 37°C. The coffee solution was prepared by mixing 2 g of coffee (Folgers Classic Roast Instant Coffee, J.M. Smucker Co., Orrville, OH) in 6 fl. oz of hot water. L*a*b* measurements were taken in the same orientations as the initial values against the white calibrated tile, and the color change was measured by ΔE2000 from the difference between the original and stained L*a*b* values.

Water sorption

Water sorption discs (n = 10/group) were prepared following the same process described for flexural strength bar preparation using dimensions similar to those specified in ISO standard 20795-1:2013 (8.9) (15 mm diameter × 1 ±0.2 mm). Specimens were immersed in 20 mL of distilled water at 37°C for 7 days. Specimens were removed, excess water was removed with a dry paper towel, dried in air for 30 seconds and the saturated mass (m_1) was recorded after 60 seconds to the nearest 0.001 g using an analytical balance (AE163, Mettler Toledo, Columbus, OH). The specimens were then

placed in a dessicator (37°C for 24 hours), then a second dessicator (24°C for 60 minutes), and re-weighed. This process was repeated until a stable weight was achieved (m_2). Water sorption was measured as ($m_1 - m_2$) / volume of the specimen.

Resin characterization

The filler weight percentage was measured using the Standard Ash Method.[27] Blocks of each material (n = 10) were placed in an alumina crucible (Coors high-alumina 20 mL crucible, Sigma Aldrich, St Louis, MO) and the weight of each block (W_0) was measured in an analytical balance (AE163). The organic matrix of each material was burned out by heating the blocks at 800°C for 30 minutes in an electric furnace. The remaining inorganic filler was then re-weighed (W_1) after drying in a dessicator until a constant weight was achieved. Filler weight percentage (wt%) was determined with the following formula: $W_1/W_0 \times 100\%$.

The organic resin composition of the 3D-printed denture materials and the heat-cured acrylic liquid were analyzed with Fourier transform infrared (FTIR) spectroscopy using an Alpha II ATR-FTIR Spectrophotometer (Bruker, Billerica, MA). The bare ATR crystal was scanned in the open air with the press open for background subtraction. The spectra were collected at 400–4,000 cm^{-1} wavelength range with 16 sample scans and 16 background scans at a resolution of 4 cm^{-1}. Spectra were baseline corrected in OPUS, min-max normalized, and displayed with a vertical offset for ease of viewing. The resins were placed directly onto the crystal and left uncured. Three specimens were prepared for each material and the spectra were compared to ensure consistency.

Statistical analysis

Due to a lack of previous data on the materials, a post-hoc power analysis was performed to ensure that the statistical tests contained adequate sample size using G*Power. A two-way ANOVA was performed for flexural strength data for factors material and testing condition (dry/wet) using SPSS software version 28 (IBM, Armonk NY). If appropriate, individual one-way ANOVAs and Tukey post-hoc analyses were performed. A one-way ANOVA was performed for fracture toughness, translucency, stain resistance, and water sorption data. A 5% significance level ($p < 0.05$) was used for all analyses.

RESULTS

The post-hoc power analysis determined all tests had adequate power (>90%). The mean and standard deviation of flexural strength, and fracture toughness are presented in Table 2. For flexural strength, a two-way ANOVA revealed significant differences for both factors of the material (p<.001) and testing condition (dry/wet) (p<.001), as well as their interaction (p<.001), allowing individual one-way ANOVAs and Tukey post-hoc analyses to be performed. Dry testing produced significantly greater flexural strength (p<.001). A one-way ANOVA determined significant differences between fracture toughness. Significant differences between materials are indicated with different letters in each column of Table 2. A plot of representative flexural strength versus displacement of the materials is presented in Figure 2. Lucitone Digital Print 3D Denture Base (wet and dry), High Impact Denture Base (wet), and Ivotion Base Milled Denture Base (dry) specimens did not break at the 20 mm maximum displacement. Three of the 3D-printed materials (Dentca Denture Base II, TrueDent Resin, and High Impact Denture Base) underwent more displacement under wet than dry conditions. The milled (Ivotion Base Milled Denture Base) and conventional (Lucitone 199) materials underwent more displacement dry than wet.

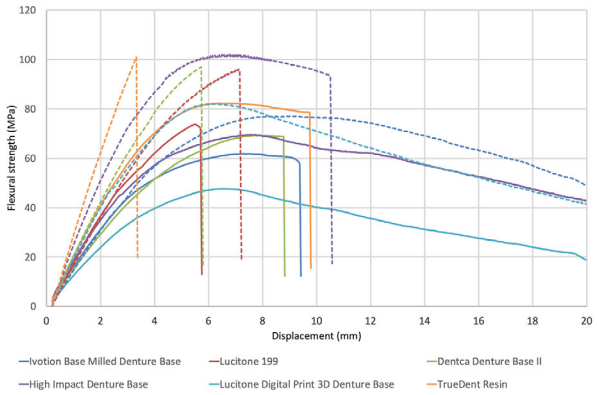

FIGURE 2 Flexural strength versus displacement of the materials used in this study. Dotted lines represent dry testing and solid lines represent wet testing.

The mean and standard deviation of translucency, stain resistance, and water sorption are presented in Table 2. A one-way ANOVA determined significant differences between translucency, stain resistance, and water sorption of different materials (p<.001), and Tukey post-hoc analyses were performed. Significant differences between materials are indicated with different letters in Table 2. Representative specimens are presented in Figure 3.

The results of the burned ash testing of filler weight percentage are presented in Table 1. Representative FTIR spectra for each material are presented in Figure 4. TrueDent Resin and Dentca Denture Base II have peaks at 1297, 1319, 1364, 1380, 1405, 1454, 1510, 1580, 1609, and 1635 cm^{-1}, which correspond to those of Bis-GMA.[28] The strong peak at 1319 also suggests the addition of TEGDMA. Lucitone Digital Print 3D Denture Base has many of the same peaks as TrueDent Resin and Dentca Denture Base II including those at 1297, 1319, and 1635 cm^{-1}, which indicate the methacrylate functional group.[28] It also contains peaks at 1497, 1510, and 1600 cm^{-1} which do not correspond to BisGMA. High Impact Denture Base has peaks at 1240, 1297, 1319, 1378, 1411, 1456, 1531, and 1635 cm^{-1}, which correspond to those of UDMA.[28]

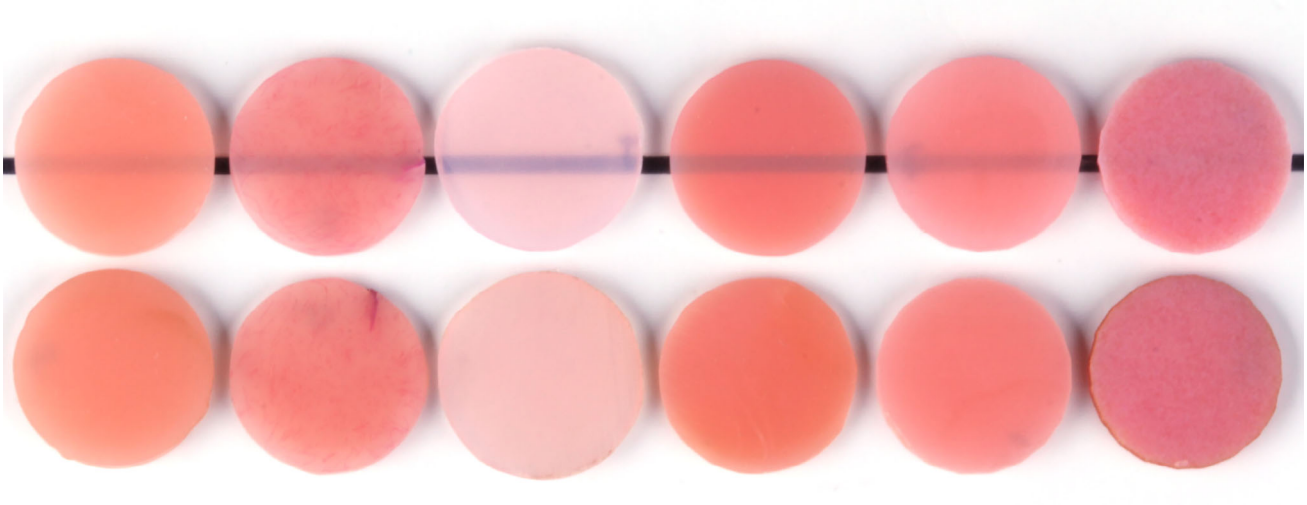

FIGURE 3 Representative specimens demonstrating translucency against a black line (top row) and color change following staining (bottom row). Materials are (left to right): Ivotion Base Milled Denture Base, Lucitone 199, Dentca Denture Base II, High Impact Denture Base, Lucitone Digital Print 3D Denture Base, TrueDent Resin.

TABLE 1 Denture base materials used in this study.

Material	Manufacturer	Fabrication method	Filler content (wt%)
Ivotion Base Milled Denture Base (Pink)	Ivoclar Vivadent	Milled	***
Lucitone 199 Denture Base Resin (Light)	Dentsply Sirona	Heat polymerized	***
Dentca Denture Base II (Light Pink)	Dentca	*DLP vat 3D-printed	***
High Impact Denture Base	Sprint Ray	*DLP vat 3D-printed	19.9 ± 1.1%
Lucitone Digital Print 3D Denture Base (Original)	Dentsply Sirona	**CLIP vat 3D-printed	***
TrueDent Resin (Pink V2)	Stratasys	Material jetting printed	4.7 ± 0.8%

*Digital light processing.
**Continuous liquid interface production.
***No filler measured (no solid remaining after ash testing).

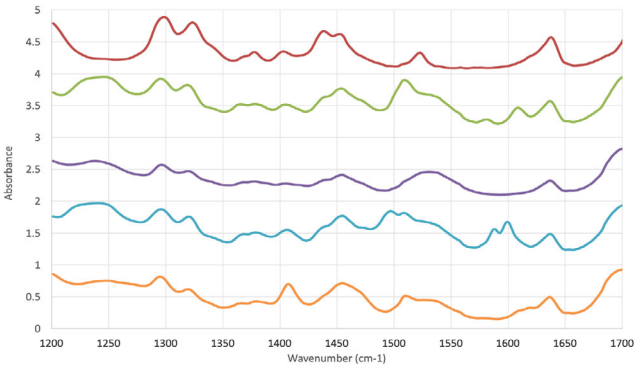

FIGURE 4 FTIR spectrum of the materials used in this study.

DISCUSSION

The null hypothesis that there would be no difference in flexural strength of denture base materials was rejected. For dry testing, one 3D-printed material (Lucitone Digital Print 3D Denture Base) and the milled denture base had a lower flexural strength than all other materials. For wet testing, the same 3D-printed material (Lucitone Digital Print 3D Denture Base) had a lower strength than the milled material. All other materials had a higher flexural strength than the milled material. These results contrast most previous studies which concluded that 3D-printed materials had a lower flexural strength than milled and conventional materials.[1–13] One difference between the current study and previous studies is that most studied older 3D-printed materials tested with in-office printers (ie Denture 3D+, NextDent; Denture Base Resin, FormLabs; and DentaBASE, Asiga) and a previous version of the milled denture base material (IvoBase CAD, Ivoclar Vivadent). Previous studies have not reported the strength of the later-generation 3D-printed denture base materials used in this study. Previous studies have reported the strength of Ivotion Base Milled Denture Base as 91 MPa (dry)[14] and 59 MPa (wet)[21] as compared to 77 MPa (dry) and 62 MPa (wet) in this study. Previous studies have reported the strength of IvoBase CAD as 70–120+ MPa (dry).[1,8,11,13] The improved strength of 3D-printed denture base materials relative to the milled and conventional denture base materials

TABLE 2 Mechanical, optical, and physical properties of the denture base materials evaluated in this study.

Material	Flexural strength (dry) (MPa)	Flexural strength (wet) (MPa)	Fracture toughness (Kic)	Translucency (ΔE2000)	Stain resistance (ΔE2000)	Water sorption (g/mm^3)
Ivotion Base Milled Denture Base (Pink)	77.01 ± 1.72^{a}	61.8 ± 3.57^{b}	1.87 ± 0.09^{b}	11.14 ± 0.57^{b}	2.37 ± 0.86^{b,c}	0.018 ± .002^{a}
Lucitone 199	96.36 ± 2.43^{b}	73.8 ± 4.23^{c}	2.03 ± 0.12^{c}	14.00 ± 1.12^{d}	2.52 ± 0.88^{b,c}	0.017 ± 0.003^{a}
Dentca Denture Base II (Light Pink)	97.03 ± 4.87^{b}	69.32 ± 5.48^{c}	0.54 ± 0.05^{a}	23.68 ± 1.29^{e}	3.31 ± 0.94^{c}	0.016 ± 0.003^{a}
High Impact Denture Base	102.40 ± 3.15^{b}	69.64 ± 4.65^{c}	1.76 ± 0.15^{b}	12.35 ± 0.80^{c}	2.31 ± 0.39^{b}	0.0017 ± 0.003^{a}
Lucitone Digital Print 3D Denture Base	82.36 ± 1.68^{a}	47.77 ± 2.26^{a}	2.01 ± 0.09^{c}	12.20 ± 0.64^{b,c}	1.30 ± 0.56^{a}	0.012 ± 0.003^{a}
TrueDent Resin	101.76 ± 7.65^{b}	82.39 ± 1.11^{d}	0.58 ± 0.05^{a}	5.13 ± 0.13^{a}	1.69 ± 0.24^{a,b}	0.061 ± 0.010^{b}

Materials in each column with different superscripts are statistically different

in this study may be related to filler content added to some resins or differences in the resin monomers.

The null hypothesis that there would be no difference in the flexural strength testing under wet and dry conditions was rejected as wet testing produced lower flexural strength. Water acts as a plasticizing agent which may interfere with the entanglement of polymer chains and allow easier chain movement.[19] As a result, the flexural strength of the materials decreased, however, their flexibility increased as evidenced by the decreased slope of the strength-displacement curves in Figure 2. The 3D-printed materials also underwent more displacement before failure which may be related to the increased flexibility caused by plasticization. Surprisingly, the milled and conventional denture base materials underwent less displacement under wet conditions. Practically, both dry and wet strength are important as dentures are wet when present in the mouth or water storage and dry during laboratory fabrication and if stored dry.

The null hypothesis that there would not be differences in fracture toughness of materials was rejected. The 3D-printed materials with the lowest fracture toughness (TrueDent Resin and Dentca Denture Base II) possessed the highest flexural strength, whereas the 3D-printed material with the highest fracture toughness (Lucitone 199 Denture Base Resin) possessed the lowest flexural strength. The fracture toughness of denture base materials was related more to the displacement before fracture and area under the strength-displacement curve (Figure 2) than the strength of the material. The materials with the lowest fracture toughness (TrueDent Resin and Dentca Denture Base II) demonstrated a lack of displacement beyond the maximum flexural strength (Figure 2), indicating brittle fracture.

Some explanation of the differences in mechanical performance of the 3D-printed resins may be offered from their composition. TrueDent Resin and Dentca Denture Base II had resin profiles of traditional Bis-GMA (low flexibility) and TEGDMA (low molecular weight) monomers which explain the relatively high strength and low flexibility. TrueDent Resin also contained some filler which may have improved its strength. Lucitone 199 Denture Base Resin had a resin profile indicating Bis-GMA and TEGDMA but also contained other strong peaks at 1497, 1510, and 1600 cm^{-1} which may be an additional type of monomer that imparted toughness. This resin was also unfilled which could explain its relatively lower strength but high flexibility. High Impact Denture Base had a resin profile which suggested the presence of UDMA, a very flexible monomer, and the presence of 20% filler. The UDMA may have imparted flexibility and the relatively high strength of the material may have been derived from its filler.

The null hypotheses that there would be no difference in translucency, stain resistance, and water sorption were all rejected. Dentca Denture Base II was significantly more translucent than other materials whereas TrueDent Resin was significantly more opaque (Table 2 and Figure 3). This outcome, as well as the results of previous studies,[22,23] indicate that translucency is a factor of the individual material, not the method in which it is fabricated. Unlike previous studies that concluded 3D-printed denture base materials stain in coffee more than conventional or milled materials,[3,24,25] the current study noted similar or less staining of 3D-printed materials as milled or conventional materials. Also unlike previous studies,[17,23] most 3D-printed materials absorbed a similar amount of water as milled or conventional materials, aside from TrueDent Resin which absorbed more. Interestingly, although TrueDent Resin absorbed significantly more water than all other materials, it did not undergo more coffee staining. The differences between the results of the current study and previous studies may be related to the individual resins used. Staining and water sorption may be related to polarity or degree of conversion of the resin or microvoids within the 3D-printed part.[17]

A limitation of the current study was that fracture toughness was only measured dry as this is the condition indicated by ISO 20795-1:2013. Another limitation of the study was that only maximum flexural strength was recorded rather than yield strength. Yield strength is the strength of a material in which further bending of a sample will cause permanent deformation. This point on a strength-displacement plot is identified when the curve transitions from a linear to a non-linear slope, which is often technically challenging to discern. Practically, the yield strength is important for a

denture as subjecting a denture to stress beyond its yield strength would permanently change its shape and potentially its fit. Future studies could measure the wet fracture toughness of these materials as well as their yield strength. Other properties of denture base materials that could be examined include surface roughness, accuracy, color stability, compatibility with reline materials, and bonding characteristics to materials used to secure attachments or other prosthetic components. Additionally, clinical trials are always necessary to validate the results of laboratory testing. For example, a clinical trial could examine different denture bases and record patient function and comfort.

CONCLUSIONS

All but one of the 3D-printed denture base materials tested in this study had similar or greater wet flexural strength as the reference milled and conventional denture bases. The strength of all denture base materials decreased when tested under wet conditions, and therefore, the wet testing protocol described in ISO 20795-1:2013 should be uniformly followed when reporting flexural strength. Some of the 3D-printed materials (Dentca Denture Base II and TrueDent Resin) tended to become brittle when tested dry which would make these materials susceptible to fracture if handled dry during storage or fabrication. The flexural strength of denture base materials did not predict their fracture toughness, and several materials with high flexural strength possessed a relatively low fracture toughness. Several of the 3D-printed denture base materials (Lucitone Digital Print 3D Denture Base and High Impact Denture Base) demonstrated high toughness and high fracture toughness which should impart favorable clinical fracture resistance. Translucency varied among different 3D-printed materials. The high translucency of Dentca Denture Base II and low translucency of TrueDent Resin may present esthetic concerns. All of the 3D-printed denture base materials stained equivalent to or less than the milled and conventional materials. Only one of the 3D-printed materials absorbed more water than the milled and conventional materials.

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