EFFECT OF DIFFERENT PRINT ORIENTATIONS ON THE FLEXURAL STRENGTH OF 3D PRINTED DENTURE BASE RESIN

A Thesis

by

CHRISTINA IRENE WANG

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Seok-Hwan Cho
Committee Members,	Jenn-Hwan Chen
	Elias Kontogiorgos
	Feng-Ming Wang
Head of Department,	Larry L. Bellinger

May 2020

Major Subject: Oral Biology

Copyright 2020 Christina Wang

ABSTRACT

Statement of problem. The introduction of additive manufacturing to the field of prosthodontics has recently made it possible to fabricate 3D printed complete dentures; however, there is limited data evaluating the flexural strength of 3D printed denture base resins and the effect of print orientation on flexural strength.

Purpose. The purpose of this in vitro study was to evaluate the effect of print orientation on flexural strength of 3D-printed denture base resin and compare it to flexural strength of compression molded denture base resin.

Materials and methods. Four groups (n=10) of denture base resins (64 mm × 10 mm × 3.3 mm) were fabricated; 10 compression molded as the control, 10 printed in a vertical orientation, 10 printed in 45˚ orientation, and 10 printed in a horizontal orientation. Specimens were stored in water for 1 week and then underwent a three-point bending test to measure flexural strength. Statistical analysis was performed using one-way analysis of variance (ANOVA) followed by the Tukey HSD post hoc test (α=.05).

Results. Average values of flexural strength for the 3D printed and control group were 100.6 ± 13.5 MPa (vertical orientation), 81.9 ± 13.1 MPa (45˚ orientation), 73.9 ± 8.5 MPa (horizontal orientation), and 82.3 ± 11.1 MPa (compression molded). There was a statistically significant difference among groups as demonstrated by one-way ANOVA (*P*<.05). The post hoc Tukey HSD test indicated that flexural strength of the vertical 3D printed group was statistically higher than 45˚ 3D printed groups (*P*=.006), the horizontal 3D printed group (*P*=.000) and the compression molded group. (*P*=.007). The test also showed no significant difference between the 45˚and horizontal 3D printed groups (*P*=.430), the 45˚ 3D printed and compression molded groups (*P*=1.000), and the horizontal 3D printed and compression molded groups (*P*=.399).

Conclusions. The vertical print orientation group produced the highest flexural strength in comparison to the 45˚ orientation group, the horizontal orientation group, and the compression molded group.

Clinical implication**.** The obtained results suggest that optimal printing orientation for denture base resin is vertical and that 3D printed denture bases may be a useful alternative to conventionally processed denture bases.

ACKNOWLEDGEMENTS

I would like to thank my thesis committee members Dr. Seok-Hwan Cho, Dr. Jenn-Hwan Chen, Dr. Elias Kontogiorgos, and Dr. Feng-Ming Wang for their guidance and encouragement. I would like to thank my previous program director, Dr. William Nagy for first believing in me and bringing me to Dallas for this residency and I would like to particularly thank my program director, Dr. Seok-Hwan Cho, for his patience and continued support in completing this thesis and throughout residency.

Thank you to my husband, Edward, for your unconditional love and patience throughout my educational journey. To my parents, Eric and Ae Yon, thank you for always supporting me and pushing me to reach my goals. Also, to my co-residents, thank you for three years of memories and pushing each other to learn and be better.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Dr. Seok-Hwan Cho, Dr. Jenn-Hwan Chen, Dr. Elias Kontogiorgos of the Department of Restorative Sciences and Dr. Feng-Ming Wang of the Department of Endodontics.

The statistical analysis was conducted in part by Dr. Elias Kontogiorgos. All other work conducted for the thesis was completed by the student independently.

Funding Sources

Funds were provided by the Office of Research and Graduate Studies at Texas A&M University College of Dentistry.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

In modern prosthodontics, polymethyl methacrylate (PMMA) is the ubiquitous and most common material of choice for complete denture fabrication,[1] however, denture base resins are subject to many different types of stresses[2] and are particularly prone to fracture.[3] Fractures remain the most common cause of failure among removable dental prostheses[4], and these fractures may occur by accidental high impact force extra-orally as a result of dropping the prosthesis[5-7] or intraorally from repeated masticatory forces leading to flexural fatigue.[8] Flexural fatigue occurs due to repeating flexing and is a mode of fracture that eventually fails due to repeated small loads.[8] Microscopic cracks develop in areas of stress concentration and with continued loading these cracks fuse to an ever-growing fissure that weakens the material.[8] A final loading cycle that exceeds the mechanical capacity of the remaining sound portion of the material results in catastrophic failure.[9] Maxillary denture fractures are typically caused by a combination of both impact and fatigue while 80% of mandibular denture fractures occurred from high-impact forces.[10]

Flexural strength of a material represents the highest bending stress at its moment of fracture,[11] which reflects its potential to resist catastrophic failure.[12] A high flexural strength of denture base resin is critical due to the gradual and irregular force distribution that occurs with alveolar absorption resulting in uneven prosthesis support.[12] A commonly used method to measure the flexural strength of denture base resins is the three-point bend test, as described by American Dental Association Standard No. 139, in accordance with International Standards Organization (ISO) 20795-1 for denture base polymers.[13]

Since its introduction in the 1970s, computer-aided design/computer-assisted manufacture (CAD/CAM) has rapidly changed the field of dentistry.[14-16] For several years CAD/CAM technology has been applied to removable prosthodontics by milling complete dentures from prepolymerized polymethyl methacralyate (PMMA) blocks.[17] Al-Dwairi et al. found that CAD/CAM PMMA specimens showed improved flexural strength, flexural modulus, and impact strength compared to conventional heat-cured methods[18] and Aguirre et al. found the flexural strength and flexural modulus of CAD/CAM milled denture base resin to be significantly higher than conventional methods.[11] Srinivasan revealed that CAD/CAM resin is equally biocompatible and showed improved mechanical properties.[19] Janeva revealed main advantages of CAD/CAM dentures to be reduced clinical chair time and number of visits, higher retention, digital archiving, and more favorable clinical and patient-centered outcomes.[20] CAD/CAM dentures have shown superior mechanical and physical properties such as enhanced fit of milled denture bases, less denture tooth movement and increased ultimate flexural strength, toughness, and higher elastic modulus.[20]

The latest wave of development in digital technology, 3-dimensional (3D) manufacturing, has continued to transform and shape modern dental practices.[21,22] In order to fabricate a physical prototype, digital data must be converted into a standard tessellation language (STL) file.[23] This data can be acquired by taking an intraoral digital impression[24] or scanning an impression or cast.[25] 3D manufacturing employs two different methods: subtractive manufacturing (SM) and additive manufacturing (AM).[26,27] SM, more commonly known as 'milling',[22] uses a cutting tool to remove material and form an object.[28] AM, also referred to as rapid prototyping or 3D printing,[28] adds material one layer at a time to build an object.[22] Stereolithography (SLA) and digital light processing (DLP) are 3D printing modalities that have been adopted in dental practice.[28] SLA uses an ultraviolet (UV) laser light to cure layers of photosensitive liquid resin onto a build platform.[26,29] SLA offers high accuracy, a smooth surface finish, and fine building details.[30,31] The DLP process involves liquid photoactivated resin that is cured by UV light onto the build platform in layers.[32] A digital micromirror device (DMD) is used to create a light mask that is projected on the resin surface.[28,33] DLP produces good accuracy, a smooth surface finish, and is relatively fast.[22]

Recently, additive manufacturing has provided an innovative method to fabricate complete dentures from the digital data.[34,35] AM has various advantages over conventional milling methods: it reduces material waste, enables fabrication of complex objects with fine detail that cannot be milled,[16,29,36,37] and with tabletop printers being more affordable than milling machines it could be more accessible to clinicians or lab technicians in lower-income areas.[38] Printed dentures have mostly been used for interim prostheses or evaluation of complete dentures,[38] but for patients with poor dexterity that are at high risk for catastrophic impact failures or for those with limited access to care, the ability to fabricate multiple dentures simultaneously[27] at a low cost could be of great use.

Unlike conventional methods, additive manufacturing methods have many variables such as light intensity, software, supporting structures, shrinkage between layers, and print orientation which could affect accuracy.[39] The print orientation can affect the build time, quality of the part, and mechanical properties of anisotropic parts[6] as the processing mechanism can lead to different polymerization patterns in a slicing software.[40-44] Vayrynen found optimal printing direction to be vertical for occlusal devices,[45] and Unkovskiy showed highest flexural strength for dental surgical guide specimens printed at 90°.[46] Shim recently found denture base resin specimens printed at 0˚ had the highest flexural strength, although the NextDent Base PMMA was printed with a third-party printer.[47]

The published data on print orientation in regards to mechanical properties of 3D printed denture base resins is limited. Therefore, the purpose of this in vitro study was to evaluate the effect of print orientation on flexural strength of 3D printed denture base resin in comparison to the flexural strength of compression molded denture base resin. The null hypotheses were that there were no differences of flexural strength values among the different print orientations of the 3D printed groups and compression molded denture base resins.

2. MATERIALS AND METHODS

2.1 3D printed fabrication

Three groups of rectangular shaped (64 mm × 10 mm × 3.3 mm) specimens (E-Denture 3D+; EnvisionTEC) were printed with a 3D printer (VIDA; EnvisionTEC). The three groups differentiated in their print orientation (10 printed in a vertical orientation, 10 printed in 45˚ orientation, and 10 printed in a horizontal orientation) and were printed with a layer thickness of 100 microns (Figure 1). Once the print job was completed, specimens were removed from the build platform and submerged in a bath of 99% isopropyl alcohol (Isopropyl Alcohol; Swan) for no longer than sixty seconds and then sprayed dry with compressed air. This was then repeated but with a second bath of clean 99% isopropyl alcohol ((Isopropyl Alcohol; Swan). Supports were removed and specimens were cured (Otoflash; EnvisionTEC) according to manufacturer's instructions.

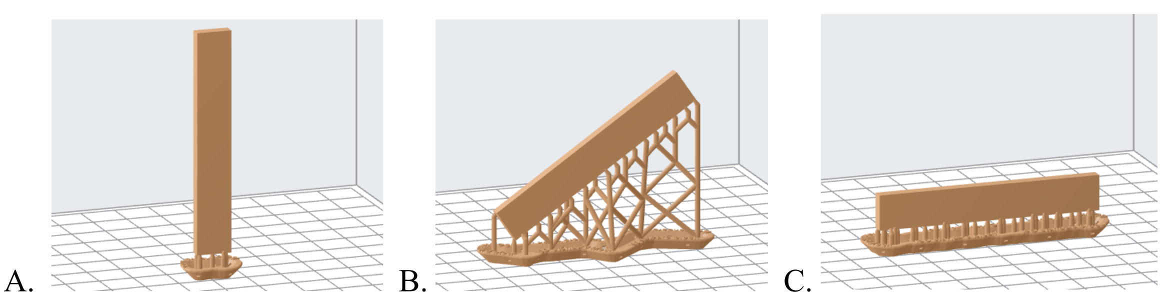

Figure 1. Print Orientations of Specimens (A. vertical orientation, B. 45˚ orientation, C. horizontal orientation)

2.2 Compression molded fabrication

From the 3D printed specimens, a vinyl polysiloxane putty (Express STD; 3M ESPE) matrix was formed in order to create wax duplicates and then pink base plate wax (Modern Materials Baseplate Wax; Kulzer GmbH) was dripped into the matrix. The 10 wax duplicates (64 mm x 10 mm x 3.3 mm) were flasked and invested with ISO type 3 dental stone (Microstone; Whip Mix Corp.) according to the manufacturer's instructions. The flask was then placed in boil out solution for 8 minutes and then after separation, the wax was flushed out with boiling solution (Patterson Boil Out Solution; Patterson Dental). The halves were cooled to room temperature and liquid tin foil substitute (Al-Cote; Dentsply Sirona) was applied to the stone and allowed to dry. Denture base resin (Lucitone 199; Dentsply Sirona) was mixed with 21 g polymer to 10 ml monomer and the jar was covered for ten minutes while material reached packing consistency. Using finger pressure, the resin was condensed into the mould and the flask was closed in a pneumatic flask press (Coe-Bilt; Nevin) under a 27 kN load. After being loaded in a spring clamp, per manufacturer instructions, the flask was placed into a water polymerization unit (Hanau Curing Unit; Hanau Engineering Company Inc) for 9 hours at 163˚F and then 30 minutes in boiling water at 212˚F. The flask was then bench-top cooled for 30 minutes and then placed in 70˚F water for 15 minutes before deflasking. Ten PMMA acrylic denture base resins were made as the control group.

2.3 Preparation of samples for flexural strength test

Specimens were visually inspected using magnifying loops to ensure no defects or irregularities were present. The specimens were then ground with wet 220-grit to 600-grit silicon carbide paper (Wetordry; 3M ESPE) and measured with digital calipers (Digital Caliper 01407A;

Neiko) to ±0.03 mm. Prior to testing, all specimens were stored in room temperature distilled water for 1 week.

2.4 Three-point bend test and measurement of flexural strength

All specimens were tested with a universal testing machine (5567 Universal Testing Machine; Instron Ltd) by using a three-point bend test per guidelines of ISO 20795-1 for denture base polymers. Each specimen was arranged on two rounded support beams with a 50 mm span. (Figure 2) A load cell was then applied to the center of each specimen with the universal testing machine (5567 Universal Testing Machine; Instron Ltd) at a crosshead speed of 5mm/min. (Figure 3) The specimen was loaded until fracture, which was the moment that the applied loads dropped to zero. The data was recorded by using a software program (Bluehill v1.5; Instron Ltd).

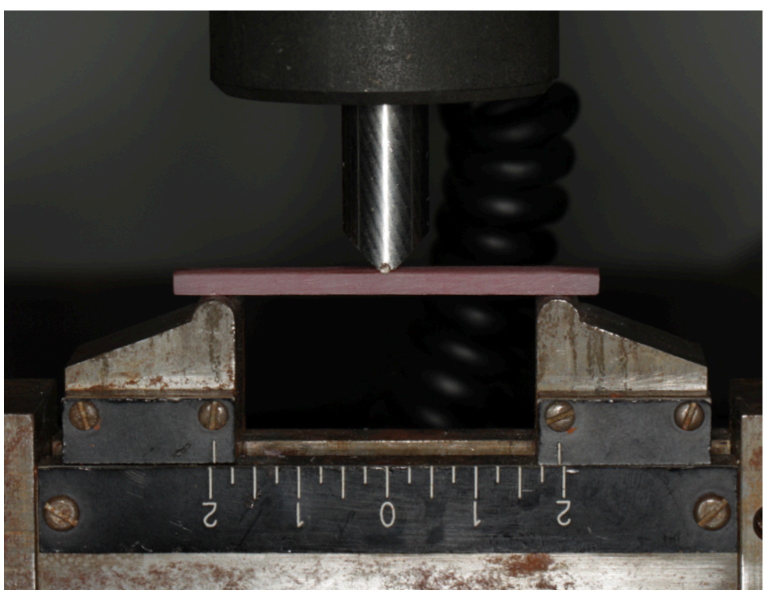

Figure 2. Three-point Flexural Test Setup

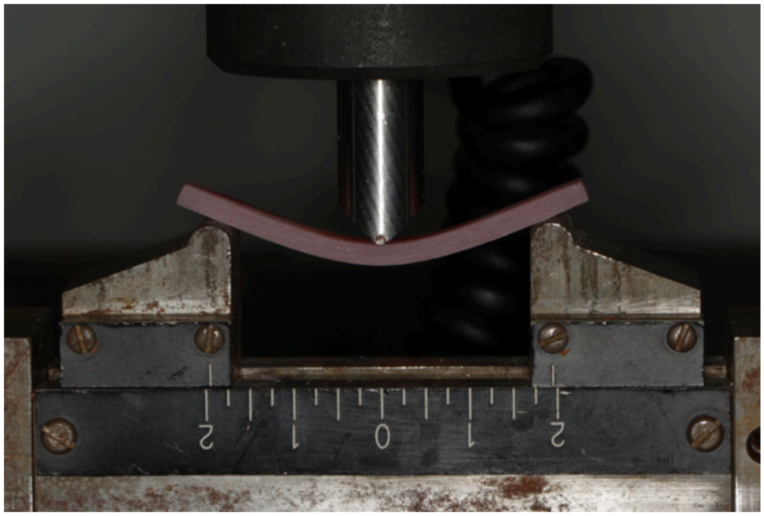

Figure 3. Deflection of Specimen Before Fracture

2.5 Calculations and statistical analysis

The flexural strength (F_s) of each specimen was then calculated with the following formula:

$$F_s = 3PL/2bd^2$$

P = load at which fracture occurred (N)   L = span length

b = specimen width   d = specimen thickness

Data was analyzed by using a statistical software program (IBM SPSS Statistics, v25.0; IBM Corp). Statistical analysis was performed with one-way analysis of variance (ANOVA) to determine whether significant differences existed among the groups, followed by the Tukey HSD post hoc test which determined which group significantly differed from the others. P values $\leq .05$ were considered statistically significant.

3. RESULTS

The flexural strength of the 3D printed specimens printed in a vertical orientation were the highest, followed by the compression molded, 45˚ print orientation, and finally the horizontal print orientation specimens. Table 1 and Figure 4 show the means ± standard deviation values of flexural strength; 100.6 ± 13.5 MPa for vertical orientation, 81.9 ± 13.1 MPa for 45˚ orientation, 73.9 ± 8.5 MPa for horizontal orientation, and 82.3 ± 11.1 MPa for compression molded.

The one-way ANOVA test revealed that there was a statistically significant ($P \leq .05$) difference among the four groups. The post hoc Tukey HSD test indicated that the flexural strength of the vertical 3D printed group was statistically higher than 45˚ 3D printed groups (P=.006), the horizontal 3D printed group (P=.000) and the compression molded group. (P=.007). The test also showed no significant difference between the 45˚and horizontal 3D printed groups (P=.430), the 45˚ 3D printed and compression molded groups (P=1.000), and the horizontal 3D printed and compression molded groups (P=.399) (Table 2).

	N	**Mean**	**STDV**	**Minimum**	**Maximum**
Vertical	10	100.6132039	13.52716003	74.18	120.05
45 Degree	10	81.97047317	13.12674185	63.58	103.42
Horizontal	10	73.94594353	8.460328462	63.31	91.5
Compression	10	82.25642948	11.05011724	69.98	104.26
Total	40	84.6965	14.99043	63.31	120.05

Table 1 Descriptive statistics for flexural strength (MPa) for the 4 groups (vertical 3D printed, 45˚ 3D printed, horizontal 3D printed, compression molded)

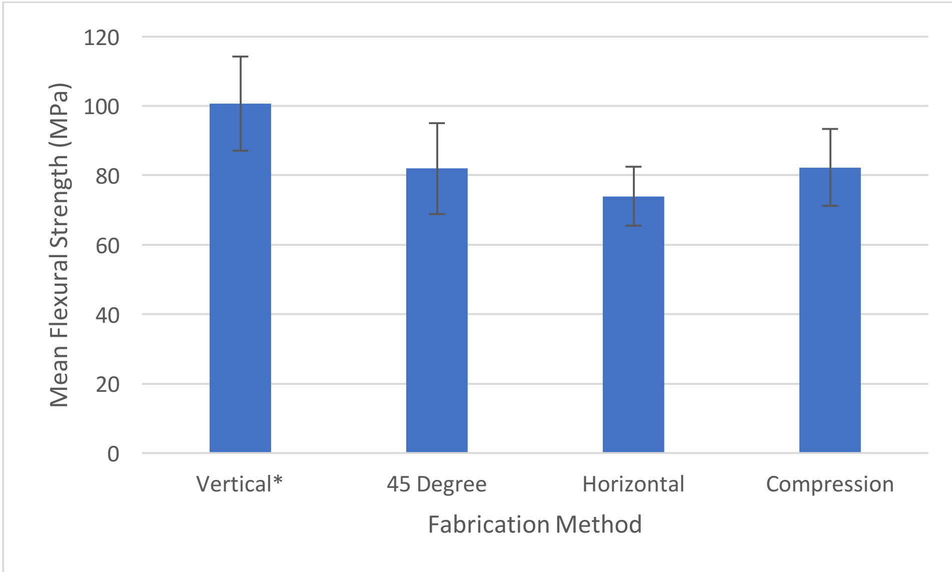

Figure 4. Mean Flexural Strength (MPa) Bar Graph (* *P* <.05)

(I) Fabrication Method	(J) Fabrication Method	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Vertical	45 Degree	18.64273*	5.23917	.006	4.5325	32.7530
	Horizontal	26.66726*	5.23917	.000	12.5570	40.7775
	Compression	18.35677*	5.23917	.007	4.2465	32.4670
45 Degree	Vertical	-18.64273*	5.23917	.006	-32.7530	-4.5325
	Horizontal	8.02453	5.23917	.430	-6.0857	22.1348
	Compression	-.28596	5.23917	1.000	-14.3962	13.8243
Horizontal	Vertical	-26.66726*	5.23917	.000	-40.7775	-12.5570
	45 Degree	-8.02453	5.23917	.430	-22.1348	6.0857
	Compression	-8.31049	5.23917	.399	-22.4208	5.7998
Compression	Vertical	-18.35677*	5.23917	.007	-32.4670	-4.2465

Table 2 Tukey HSD Post Hoc Test Results

4. DISCUSSION

Stereolithography is an additive manufacturing technique in which a photopolymerization process selectively cures a liquid material into layers of solid material, building a 3D object layer by layer.[48] With additive manufacturing, changing the print orientation is one factor the operator can control. The present study investigated the effect of different print orientations on the flexural strength of 3D printed denture base resins. The results demonstrated significant differences in flexural strength among the groups, thus allowing rejection of the null hypotheses.

Flexural strength of denture base resins is a crucial property,[12] which according to the international standards for polymer materials and International Standards Organization (ISO) 20795-1 for denture base polymers, should be no less than 65 MPa.[13] Although the flexural strength of 3D printed specimens in the current study were not as high as the flexural strength of milled denture base resin, which was found to be 146.6 MPa,[11] all samples in the present study met the International Standards Organization (ISO) requirement. By using that standard, all of the groups in the current study are acceptable for clinical use.

The results also demonstrated that denture base resin printed in a vertical orientation had a significantly higher flexural strength compared to other printed groups and compression molded methods and suggest that print orientation is a factor to consider when fabricating complete denture by 3D printed methods. While there is limited published data evaluating flexural strength of 3D printed denture base resins, these results are in disagreement with a previous study that evaluated various parameters affected by print orientation of 3D printed denture base resin.[47] Shim concluded that print orientation significantly influenced printing accuracy, flexural strength, roughness, and response to *C. albicans*.[47] Unlike the present results, he found that specimens printed horizontally had the highest flexural strength.[47] The specimens were made with NextDent Base PMMA but printed from a different third-party printer.[47] It should be noted that there are numerous parameters that can vary depending on the material and printer used, and thus interfering with the quality of printed products. The samples were also fabricated with dimensions according to International Standards Organization (ISO) 178 with dimensions of 80 mm × 10 mm × 4 mm which is different from the International Standards Organization (ISO) 20795-1 for denture base polymers.

In the present study, parallel 3D printed layers in relation to the applied load did exhibit a composition better able to resist fracture. These results indicated that vertically printed specimens had the highest fracture resisting ability and that different print orientations do affect the load bearing capacity of 3D printed denture base resins. The vertically printed specimens exhibited the highest flexural strength, with a mean of 100.61 MPa, while the 45˚ printed specimens had a mean of 81.97 MPa and the horizontally printed group 73.95 MPa. This supports the idea that layers which are perpendicular to the load being applied exhibit a weaker resistance to fracture. The print orientation has been shown to affect the adhesion between cured layers.[47,49] This phenomenon can be referred to as anisotropy, which implies that the properties of a material are directionally dependent. Unkovskiy revealed the anisotropical behavior of printed surgical guide resin and found specimens printed with a 90˚ orientation to had a higher flexural strength than 45˚ and 0˚ print orientation specimens.[46] Vayrynen also found anisotropicity of the flexural properties of occlusal devices, and found optimal printing orientation to be vertical which demonstrated the materials ability to best resist fracture.[45]

Printing objects in a more vertical orientation allows for fabrication of more products simultaneously as more objects can fit onto the print bed.[47] This saves overall print time, decreases time spent post-processing with less print cycles, and overall allows for improved efficiency.[47] In a clinical setting, this would suggest that optimal printing direction for dentures is vertical. But, mechanical properties are just one factor to consider in regards to printing denture bases. Jin recently found that in terms of tissue adaptation, optimal build angle for printed denture bases was 135˚ in the maxilla and 100˚ in the mandible.[50] Printing the denture base in a vertical orientation would also allow support structures to avoid the intaglio surface and areas where the denture teeth will be bonded.

If a resin demonstrates a higher flexural strength it may be less likely to fracture during function or when subjected to an external high impact force, such as accidentally dropping the denture. For patients with limited access to care, poor dexterity leading to multiple accidental fractures, or heavier functional loads, a 3D printed denture base may be a useful alternative to conventional denture processing methods. It should be noted that the compression molded specimens did also exhibit a mean flexural strength of 82.26 MPa which was slightly higher than that of the 45˚ and horizontally printed specimens, although this was not statistically significant. Also, although the vertically printed specimens had the highest flexural strength, all other groups still exhibited a flexural strength appropriate for clinical use.[13]

Limitations of the current study were the difference in shape between the specimens tested and a denture base used in a clinical setting. The specimens did not take into account anatomic characteristics of the residual ridge or distortion and compression of the soft tissue. Therefore, further studies investigating the mechanical properties of 3D printed denture bases fabricated with different print orientations are warranted. Also, the present study did not take into account other factors such as the effect of print layer thickness or distribution of support structures. The denture base resin was also evaluated in vitro which does not simulate the oral environment. There was also a lack of thermocycling and cyclic loading prior to the three-point bend test. It has been shown that Lucitone 199 samples did have a lower flexural strength after being thermocycled[51] and cyclic loading would better replicate an intra-oral environment. Vayryen found water storage to have a greater effect on the flexural properties of 3D printed occlusal device material than different print orientations.[45] In order to better simulate intra-oral conditions, the specimens in the current study were placed in water for one week prior to undergoing testing. In addition, different printers and different materials may exhibit different results, therefore further studies and development of proper parameters and protocols for complete dentures fabricated by additive manufacturing are needed.

5. CONCLUSIONS

Within the limitations of this in vitro study, specimens printed in a vertical orientation exhibited the highest flexural strength in comparison to 45˚ and horizontal print orientations. There was no statistically significant difference among the 45˚ print orientation, horizontal print orientation, and conventionally processed group.

REFERENCES

1. Phoenix RD. Denture Base Materials. Dent Clin North Am 1996;40:113-120.
2. Zappini G, Kammann A, Wachter W. Comparison of fracture tests of denture base materials. J Prosthet Dent 2003;90:578-85.
3. Kelly, E. Fatigue failure in denture base polymers. J Prosthet Dent 1969;21:257-66.
4. Darbar UR, Huggett R, Harrison A. Denture fracture—A survey. Br Dent J 1994;176,342-5.
5. Kaine T, Fujii H, Arikawa H, Inoque K. Flexural properties and impact strength of denture base polymer reinforced with woven glass fibers. Dent Mater 2000;16:150.
6. Hargreaves AS. The prevalence of fractured dentures. A survey. Br Dent J 1969;126:451-5.
7. Faot F, Costa MA, Cury AA, et al: Impact strength and fracture morphology of denture acrylic resins. J Prosthet Dent 2006;96:367-73.
8. Jagger DC, Harrison A, Jandt KD. The reinforcement of dentures. J Oral Rehabil 1999;26:185.
9. Wiskott HW, Nicholls JI, Belser UC. Stres fatigue: basic principles and prosthodontic implications. Int J Prosthodont 1995;8:105-16.
10. Sasaki H, Hamanaka I, Takahashi Y, et al: Effect of long-term water immersion or thermal shock on mechanical properties of high-impact acrylic denture base resins. Dent Mater J 2016;35:204-9.
11. Aguirre B, Chen JH, Kontogiorgos E, et al: Flexural strength of denture base acrylic resins processed by conventional and CAD-CAM methods. J Prosthet Dent. doi: 10.1016/j.prosdent.2019.03.010.

12. Diaz-Arnold AM, Varags MA, Shaull RL, et al: Flexural and fatigue strengths of denture base resin. J Prosthet Dent 2008;100,47-51.
13. ADA. ANSI/ADA Standard No. 139 (ISO 20795-1), Denture Base Polymers. American Dental Association; 2013. Available at: https://webstore.ansi.org/Standards/ISO/ISO207952013?gclid=EAIaIQobChMI5eGNoJ_64AIT57 ACh0YsAsyEAAYAiAAEgKeaPD_BwE.
14. Duret F, Preston JD. CAD/CAM imaging in dentistry. Curr Opin Dent 1991;1:150-4.
15. Miyazaki T, Hotta Y, Kunii J, et al: A review of dental CAD/CAM: Current status and future perspectives from 20 years of experience. Dent Mater J 2009;137:1289-96.
16. Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: Current systems and future possibilities. J Am Dent Assoc 2006;137:1289-96.
17. Bidra AS, Taylor TD, Agar JR. Computer-aided technology for fabricating complete dentures: systematic review of historical background, current status, and future perspectives. J Prosthet Dent 2013;109:361-6.
18. Al-Dwairi ZN, Tahboub KY, Baba NZ, Goodacre CJ. A Comparison of the Flexural and Impact Strengths and Flexural Modulus of CAD/CAM and Conventional Heat-Cured Polymethyl Methacrylate (PMMA). J Prosthodont 2018 June 13. doi: 10.111/jopr.12926.
19. Srinivasan H, Gjengedal M, Cattani-Lorente M, et al: CAD/CAM milled complete removable dental prostheses: an in vitro evaluation of biocompatibility, mechanical properties, and surface roughness. Dent Mater J 2008;37:526-33.
20. Janeva N, Kovacevska S, Elencevsky S, et al: Advantages of CAD-CAM versus conventional complete dentures—a review. J Med Sci 2018;6:1498-502.

21. Nayar S, Bhuminathan S, Bhat WM. Rapid prototyping and stereolithography in dentistry. J Pharm Bioallied Sci 2015;7:216-9.
22. Dawood A, Marti Marti B, Sauret-Jackson V, et al: 3D printing in dentistry. Br Dent J 2015;219:521-9.
23. Oropallo W, Piegl LA. Ten challenges in 3D printing. Eng Comput 2016;32:135-48.
24. Chochlidakis KM, Papaspyridakos P, Geminiani A, et al: Digital versus conventional impressions for fixed prosthodontics: a systematic review and meta-analysis. J Prosthodont 2016;116:184-90.e12.
25. Wesemann C, Muallah J, Mah J: et al: Accuracy and efficiency of full-arch digitalization and 3D printing: A comparison between desktop model scanners, an intraoral scanner, a CBCT model scan, and stereolithographic 3D printing. Quintessence Int 2017;48:41-50.
26. Liu Q, Leu CL, Schmitt SM. Rapid prototyping in dentistry: technology and application. Int J Adv Manuf Technol 2006;29:317-35.
27. Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prosthodontics: a review of the available streams. Int J Dent 2014;2014:78948.
28. Alharbi N, Wismeijer D, Osman R. Additive manufacturing techniques in prosthodontics: Where do we currently stand? A critical review. Int J Prosthodont 2017;30:474-84.
29. Torabi K, Farjood E, Hamedani Sh. Rapid prototyping technologies and their applications in prosthodontics, a review of the literature. J Dent Shira Univ Med Sci 2015;16:1-9.
30. Camardella LT, Breuning H, de Vasconcellos Vilella O. Accuracy and reproducibility of measurements on plaster models and digital models created using an intraoral scanner. J Orofac Orthop 2017;78:211-20.

31. Melchels FP, Feijen J, Grijpma DW. A review on stereolithography and its applcations in biomedical engineering. Biomaterials 2010;31:6121-30.
32. Andersen UV, Pedersen DB, Hansen HN, et al: In-process 3D geometry reconstruction of objects produced by direct light projection. Int J Adv Manuf Technol 2013; 68:565-73.
33. Mitteramskogler G, Gmeiner R, Felzmann R, et al: Light curing strategies for lithography-based additive manufacturing of customized ceramics. Add Manuf 2014;1-4:110-18.
34. Chung YJ, Park JM, Kim TH, et al: 3D printing of resin material for denture artificial teeth: Chipping and indirect tensile fracture resistance. Materials 2018;11:1798.
35. Kwak YH, Lee SH, Lee GJ, et al: Artificial teeth displacement of monolithic complete denture manufactured by 3D printer and milling machine. J Korean Acad Prosthodont 2017;55:394-402.
36. Azari A, Nikzad S. The evolution of rapid protoytyping in dentistry: a review. Rapid Prototyping J 2009;15:216-25.
37. Berman B. 3-D printing: The new industrial revolution. Business Horizons 2012;55:155-62.
38. Kalberer N, Mehl A, Schimmel M, et al: CAD/CAM milled versus rapidly-prototyped (3D-printed) complete dentures: an in vitro evaluation of trueness. J Prosthet Dent 2019;121:637-43.
39. Lee S, Hong SJ, Paek J, et al: Comparing accuracy of denture bases fabricated by injection molding, CAD/CAM milling, and rapid prototyping method. J Adv Prosthodont 2019;11:55-64.
40. Ide Y, Nayar S, Logan H, et al: The effect of the angle of acuteness of additive manufactured models and the direction of printing on the dimensional fidelity: clinical implications. Odontology 2017;105:108–15.

41. R. Osman, N. Alharbi, D. Wismeijer. Build angle, does it have an influence on the accuracy of 3D-printed dental restorations using digital light-processing technology? Int. J. Prosthodont 2017;30:182-8.

42. Tahayeri A, Morgan M, Fugolin AP, et al: 3D printed versus conventionally cured provisional crown and bridge dental materials. Dent Mater 2018;192-200.

43. Alharbi N, Osman R, Wismeijer D. Factors influencing the dimensional accuracy of 3D-printed full coverage dental restorations using stereolithography technology. Int. J. Prosthodont 2016;29:503-10.

44. 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;115:760-7.

45. Vayrynen VO, Tanner J, Vallittu PK. The anisotropicity of the flexural properties of an occlusal device material processed by stereolithography. J Prosthet Dent 2016;116:811-7.

46. Unkovskiy A, Bui PH, Schille C, et al: Objects build orientation, positioning, and curing influence dimensional accuracy and flexural properties of stereolithographically printed resin. Dent Mater 2018;34:e324-33.

47. Shim JS, Kim JE, Jeong SH, et al: Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations. J Prosthet Dent doi: 10.1016/j.prosdent.2019.05.034.

48. Green B, McLeod R, Guymon A. Improving anisotropic properties of objects printed via stereolithography. Composites Part B Engineering 99 doi:10.1016/j.compositesb.2016.06.009.

49. Puebla K, Arcaute K, Guintana R, et al: Effects of environmental conditions, aging, and build orientations on the mechanical properties of ASTM type I specimens manufactured via stereolithography. Rapid Prototyp J 2012;18:374-88.

50. Jin MC, Yoon HI, Yeo IS, et al: The effect of build angle on the tissue surface adaptation of maxillary and mandibular complete denture bases manufactured by digital light processing. J Prosthet Dent doi: 10.1016/j.prosdent.2018.12.014.

51. Machado AL, Puckett AD, Breeding LC, et al: Effect of thermocycling on the flexural and impact strength of urethane-based and high-impact denture base resins. Gerodontology 2012;29:e318-23.