COMPARISON OF DENTURE TOOTH POSITION DISCREPANCY AMONG DIFFERENT 3D PRINTING FABRICATION METHODS

A Thesis

by

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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

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May 2019

Major Subject: Prosthodontics

ABSTRACT

Statement of problem. 3D-printed denture workflows have been introduced and are continuing to emerge in modern dentistry, however there are few studies evaluating the effect on denture tooth position when using 3D-printing fabrication techniques.

Purpose. The purpose of this in vitro study was to investigate the tooth positional discrepancy of dentures made by 3D-printing technology.

Material and methods. A stone cast of an edentulous maxilla was selected and scanned by a laboratory scanner to generate a total of 30 maxillary dentures (n=10 per group); 3D-printed denture bonded with card teeth (CT), monolithic 3D-printed denture (MP), and 3D-printed denture bonded with 3D-printed teeth (PT). The assembled specimen scan files of each denture were aligned by using a software program for 3D analysis. Measurements were made at 64 locations, allowing evaluation of denture tooth discrepancy in an occlusal, buccal, lingual, and mesial-distal direction. In addition, posterior and anterior regions were compared in terms of tooth discrepancy. The median and interquartile range values were used to assess accuracy and reproducibility. Levene and Kruskal-Wallis statistical tests were used to evaluate differences among the three groups.

Results. For the overall tooth discrepancy analysis, there were statistically significant differences among all three groups ($P<.05$). The monolithic 3D-printed denture group showed the lowest tooth discrepancy, followed by 3D-printed denture bonded with card teeth, and 3D-printed denture bonded with 3D-printed teeth. For directional discrepancy analysis, the values of occlusal tooth discrepancy were significantly larger than the other three types of discrepancy for all three groups (*P* <.05). No significant difference between posterior and anterior region discrepancies was demonstrated (*P* >.05).

Conclusions. Monolithic 3D-printed dentures produced the highest values of accuracy and reproducibility in comparison with 3D-printed denture bonded with card teeth and 3D-printed denture bonded with 3D-printed teeth. The values of occlusal tooth discrepancy were significantly larger than the other three directions of tooth discrepancy.

ACKNOWLEDGEMENTS

I would like to thank all my co-residents, faculty, and staff over the years who have continually kept me motivated to improve as a clinician, researcher, and friend.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a thesis committee consisting of Dr. Seok-Hwan Cho, committee chair, of the Department of Restorative Sciences; Dr. William W. Nagy of the Department of Restorative Sciences; and Dr. David F. Murchison, of the Department of Diagnostic Sciences.

The data analysis was provided by Dr. Elias I. Kontogiorgos. All other work conducted for the thesis was completed by the student independently.

Funding Source

Graduate study was supported by a research grant from Texas A&M University.

NOMENCLATURE

CECD	Computer Engineered Complete Denture
STL	Standard Tessellation Language
DLP	Digital Light Processing
BSP	Blue Sky Plan®
MM	Meshmixer
IPA	Isopropyl Alcohol
CAD/CAM	Computer Aided Design/Computer Aided Manufacturing

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1. INTRODUCTION

It has been well documented in prosthodontic literature that denture teeth move during conventional flasking and processing procedures with maxillary dentures distorting more than mandibular dentures.[1-3] Denture tooth position discrepancy in conventional processing is affected by the pressure[4] used to inject or pack acrylic resin, the composition of the gypsum investment and its associated setting expansion,[5] the thickness of the denture base,[6] and water absorption.[7]

The topic of computer engineered complete dentures (CECD) has become increasingly mainstream in the realm of prosthodontics and general dentistry. CECDs are appealing to many practitioners due to their use of in-office fabrication methods which do not require manual tooth setting in wax, mounting of stone casts, and acrylic resin denture processing in flasks. Another appealing aspect for many practitioners is reducing the number of office visits required for complete removable dental prostheses. Many CECD protocols require only 3 office visits, suggesting a definitive impression and interocclusal relation record appointment, a try-in or verification appointment, and a delivery appointment.[8-10] This workflow can be accomplished with varying degrees of success depending on case selection, laboratory resources, and operator experience. Keeping these points in mind, it is not difficult to understand why a practitioner may be inclined to convert part or all their denture practice to CECD.

Computer numerical controlled (CNC) milling of polymethyl methacrylate (PMMA) pucks gave rise to the first clinically acceptable fabrication of virtually designed complete dentures.[11] Many studies have been published supporting the chemical and physical property advantages of milled PMMA for denture bases as well as an equal or superior internal fit. One drawback however to milled complete dentures may be the inability of the milling process to produce highly detailed occlusal anatomy. While milling remains the most clinically advantageous method of fabricating CECD,[12,13] the technological wave of affordable 3D-printing has reached the dental field. The low-price point and low maintenance costs of today's desktop resin 3D printers compared to those of milling machines allows more practitioners to comfortably start incorporating digital dentistry into their practice with printed wax up models, surgical guides, and custom trays. Additional printing resins for new or different applications are continually being produced and marketed to dental professionals specifically. It is becoming more and more likely that a dentist who owns a 3D-printer will venture out and try to capitalize on all the features and capabilities of the machine. It stands to reason that 3D-printed dentures will be something that any dentist with a printer will eventually try. The subsequent concern to clinicians will be what methods and workflows to choose to have the most predictable results with as little further monetary investment and risk as possible.

There are many ways to fabricate dentures by using varied combinations of analog and digital workflows. Kattadiyil et al[14] showed in a systematic review the complications associated with CECD workflows, with the lack of a trial placement and difficulty in reading certain digital previews being a common problem. 3D- printing can be used in multiple digital/analog workflows,[15] however the following three 3D-printing methods seem to be the most practical and popular: 1) A 3D-printed denture base with sockets for bonding carded teeth 2) A 3D-printed denture base with sockets for bonding printed teeth 3) A 3D-printed monolithic combination of denture base and teeth. When processing a denture, regardless of the method, excellent soft tissue adaptation of the intaglio, clean denture tooth surfaces, a dense base with no voids, and minimal to no shifting of denture teeth after processing should be goals taken into consideration.

The ideal denture processing or fabrication technique should not significantly alter the position of posterior centric contacts, esthetic occlusal planes, or the occlusal vertical dimension (OVD). Slight positive discrepancies in occlusal tooth position can compound and may cause clinically significant changes in OVD.[4] Denture fabrication techniques such as milling which do not require compression have the potential to reduce the occlusal discrepancy of posterior denture teeth.[7] Much care, skill, and judgment is put into denture tooth set ups, often with custom input specifically from the patient, so it is crucial that tooth set up remain virtually unchanged after final denture processing or fabrication. Goodacre et al[7] compared the denture tooth discrepancy of three different analog and two different CAD/CAM denture fabrication methods. The results of this study concluded that when considering both accuracy and reproducibility, CAD/CAM milled monolithic dentures ranked the highest. CAD-CAM-milled dentures can produce minimal denture tooth discrepancy by eliminating many of the known causes of processing distortion.

There are relatively few studies evaluating 3D printed denture tooth discrepancy. Thus, the purpose of the present study was to examine the proximity to zero of discrepancy value and the range of those discrepancy values, (accuracy and reproducibility), of definitive denture tooth positions in three different 3D-printed denture fabrication methods. The null hypothesis is there is no significant difference in the accuracy and reproducibility of the denture tooth position among the three 3D-printed denture fabrication methods.

2. MATERIAL AND METHODS

A stone cast of an edentulous maxilla closely approximating what is considered to be a typical type A presentation[16] according to the American College of Prosthodontics was selected and scanned by a laboratory scanner (D900/900L; 3Shape). A standard tessellation language (STL) file of this master cast was generated (Figure 1).

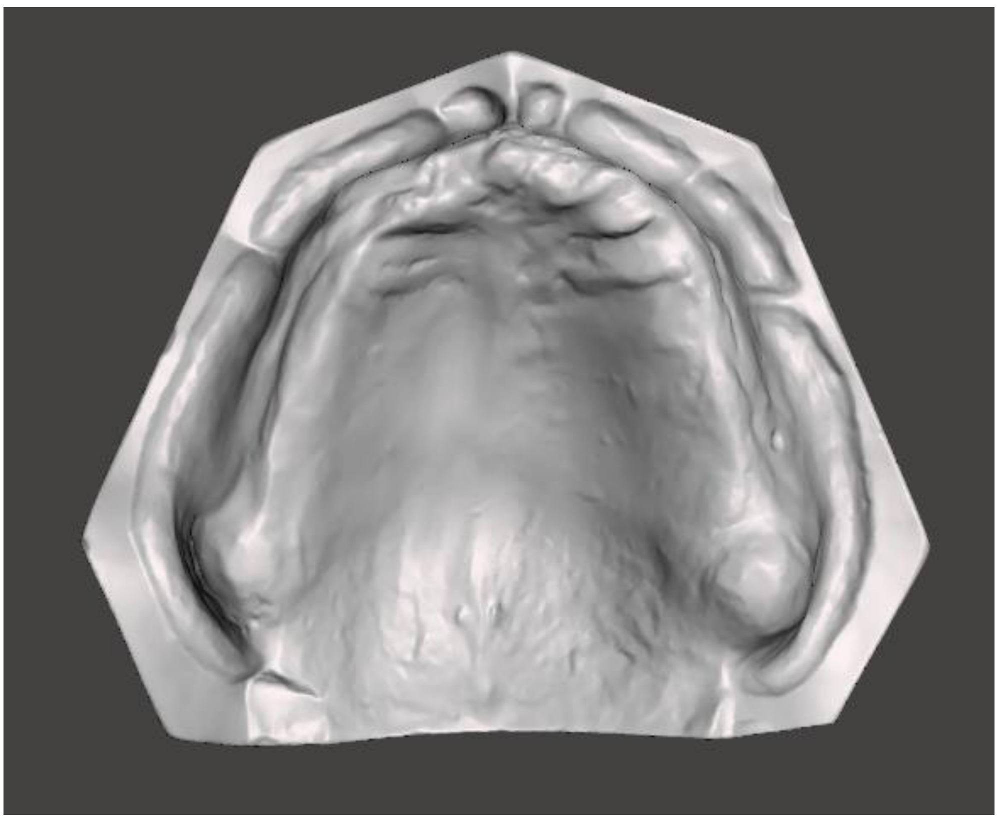


Figure 1. STL of master cast.

A digital denture tooth set up for card and printed denture teeth was arranged in a virtual planning software program (Blue Sky Plan®; Blue Sky Bio LLC). Once the set up was completed, the software was used to outline a base area and generate the denture base and cutout sockets where the teeth overlapped with the base. The tooth set up was intentionally designed not to contact the master cast STL and allow for no alteration to the physical denture teeth. The denture design was exported as separate STL files of the denture teeth and final denture base. These STL files were imported into CAD software (Meshmixer (MM); Autodesk), where STL's of 3 mm spheres were combined with the cameo surface of the STL denture base at the area of the incisive papilla and bilaterally apical to the molar areas (Figure 2). These spheres were used to aid in registration and alignment of the STL files of the printed specimens and master denture design during 3D analysis. The planning software's surgical guide module was used to create a seating jig STL file for positioning of individual denture teeth into the printed denture base. All STL files were printed using a desktop digital light processing (DLP) printer (MoonRay-S; SprintRay Inc.).

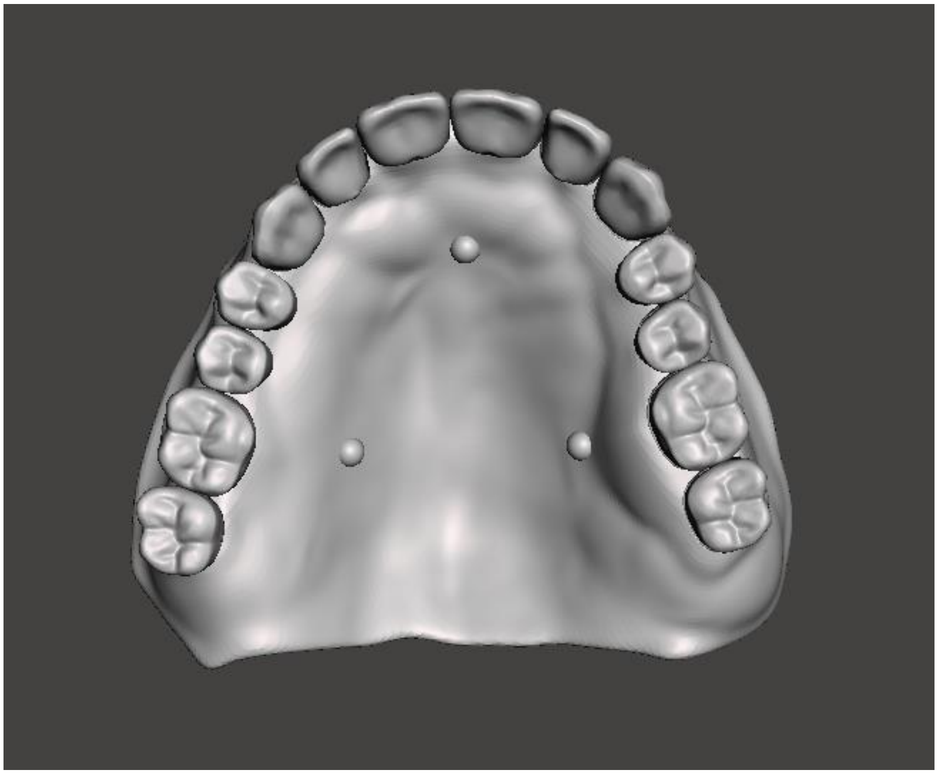


Figure 2. STL of master digital denture design with 3mm alignment spheres.

Three different 3D-printing protocols were used to fabricate dentures from the same STL files; 1.) Card teeth (CT) group: 3D-printed denture base with sockets for bonding carded teeth 2.) Monolithic print (MP) group: 3D-printed monolithic combination of denture base and teeth 3.) Printed teeth (PT) group: 3D-printed denture base with sockets for bonding printed teeth. The protocol for the CT group consisted of printing the final denture in pink base resin (NextDent™ Base; Vertex-Dental B.V.) and bonding card teeth (Nobildent acrylic teeth; Nobilium- Division of CMP Industries LLC) with the same pink base resin. The denture bases were printed with all supports located on the intaglio and border areas not used in analysis (Figure 3a and 4a). The teeth were positioned into the seating jig printed in clear resin (NextDent™ Ortho Clear; Vertex-Dental B.V.) (Figure 4d), pink base resin applied to the sockets, the assembly seated by a single operator onto the printed denture base, and light cured for 20 seconds from the buccal, intaglio, and palatal aspects in each sextant. Care was taken to minimize and remove any flash resin on the palatal and occlusal surfaces of the denture teeth. Secondly, the protocol for the MP group consisted of printing the combined STL files of the denture teeth and final denture base. The monolithic dentures were printed in dental crown resin (NextDent™C&B; Vertex-Dental B.V.) with all supports located on the intaglio and border areas not used in analysis (Figure 3c and 4c). Finally, the protocol for the PT group was similar to the CT group except that printed teeth were not positioned in the seating jig, but rather seated with firm finger pressure by the same single operator as two groups of connected teeth. The teeth were printed in dental crown resin (NextDent™C&B; Vertex-Dental B.V.) with minimal to no supports located on occlusal and lingual surfaces used for analysis (Figure 3b and 4b). All printed materials were post processed according to the manufacturer's instructions with isopropyl alcohol (IPA) washes and UV light curing.

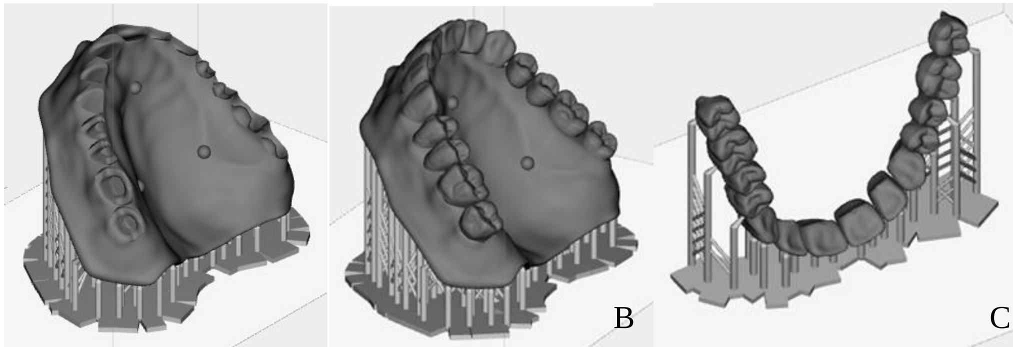


Figure 3. Print orientation and supports of specimens. a. denture base, b. monolithic denture, c. denture teeth..

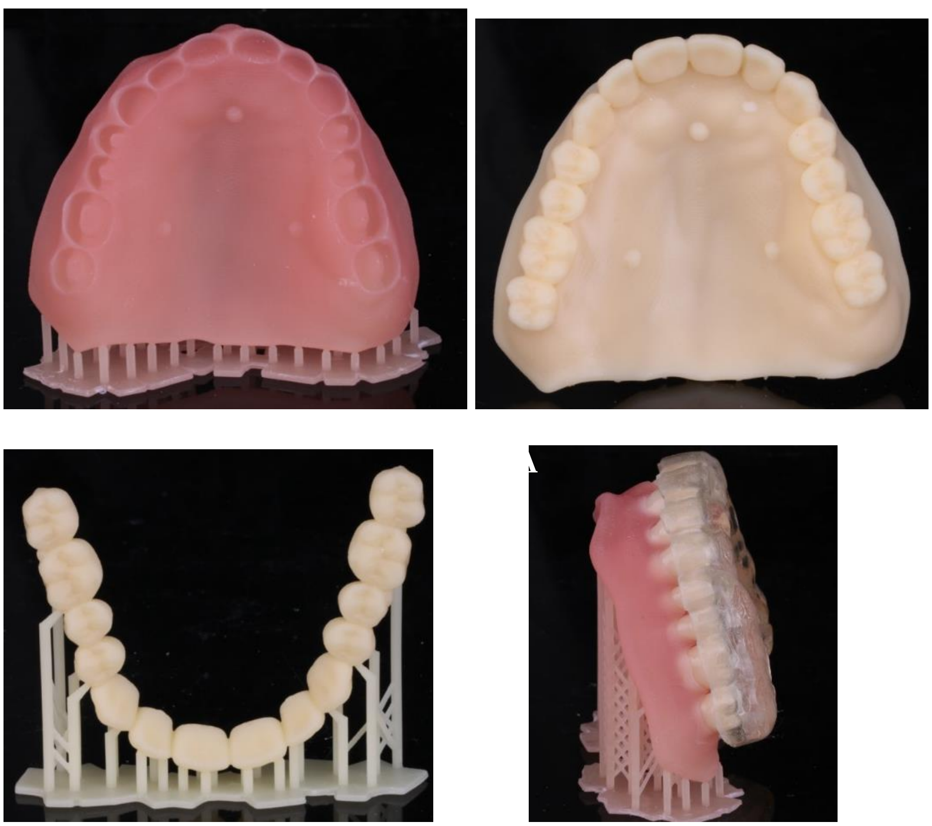


Figure 4. Printed specimens: a. denture base, b. monolithic denture, c. denture teeth, d.teeth in printed jig.
A

All specimens were scanned after final assembly and bonding of teeth (Figure 5).

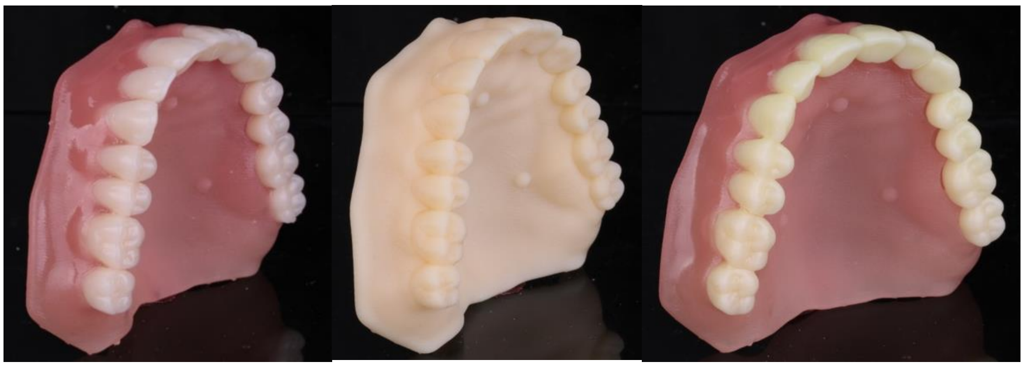


Figure 5. Final denture specimens: a. CT group, b. MP group, c. PT group.

Specimens were coated with a thin layer of CAD spray (Renfert-Scanspray; Renfert GmbH) and scanned using a laboratory scanner rated for accuracy to 7 microns (D900/900L;3Shape). The master digital STL files of the complete denture design with teeth and base were imported into Geomagic Control software (3D Systems). The protocol for measuring denture tooth discrepancy proposed by Goodacre et al[12] was followed for this study. A total of 64 points of measurement with a 1mm diameter were chosen for all 30 specimens. 3D compare color maps were created with ± 500 µm and ± 20 µm as the maximum critical and maximum nominal value, respectively (Figure 6). The denture teeth were then able to be evaluated for discrepancies in the occlusal, buccal, lingual, and mesial directions. The buccal-lingual directions were separated into 2 groups to evaluate the tendency of teeth to move in a buccal vs. lingual direction.

Mesial-distal discrepancy was not separated because of the inability to make multiple measurement points on direct mesial-distal surfaces of the denture teeth.

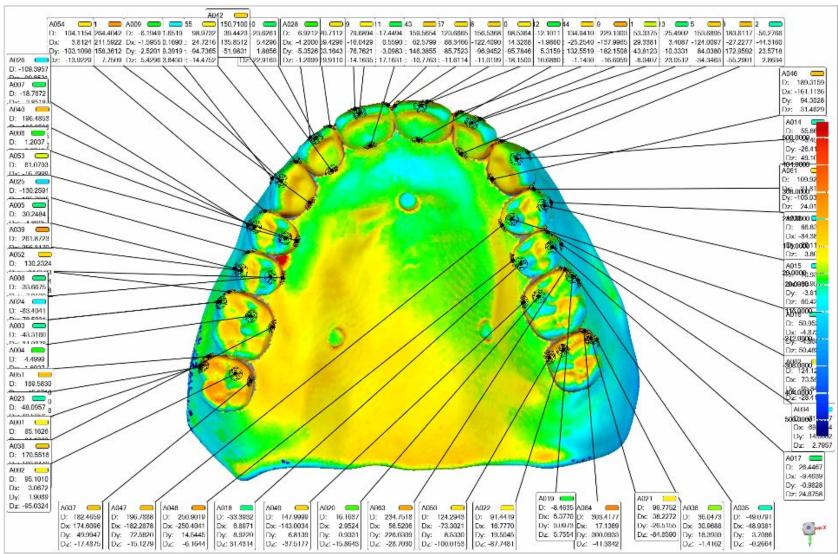


Figure 6. Geomagic control software with 64 annotation points for measurement.

The Levene test revealed a significant difference in variances between the techniques and Kruskal-Wallis procedure was used to analyze the differences between the denture tooth discrepancies recorded in each processing technique. The median value of the data represents the accuracy of the technique while the interquartile range can be used to interpret the reproducibility.

Discrepancy values generated from the 3D comparison program were then recorded in Microsoft Excel and modelled in an appropriate statistics program suite (SPSS; IBM) The discrepancies in each type of tooth movement were summarized, then the average total tooth discrepancy for each specimen was made. Differences in type of movement discrepancies between different groups were evaluated with the Mann-Whitney U test.

3. RESULTS

Figure 7 shows the qualitative analysis result of three groups (MP, CT, and PT) with color maps. Blue color mapping (negative discrepancies) shows areas of the test object that are underneath or behind the reference object while yellow to red color mapping (positive discrepancies) shows areas that are above or in front of the reference object. For the CT group, there were blue marks on molars and red and orange color marks on premolars and anteriors. For MP group, there were even blue color marks on the occlusal surface, which means monolithic printed denture teeth moved slightly below the reference object. However, for PT group, there were strong red marks on occlusal surface of all molars and premolars, indicating the PT denture teeth had positive discrepancies on the occlusal areas.

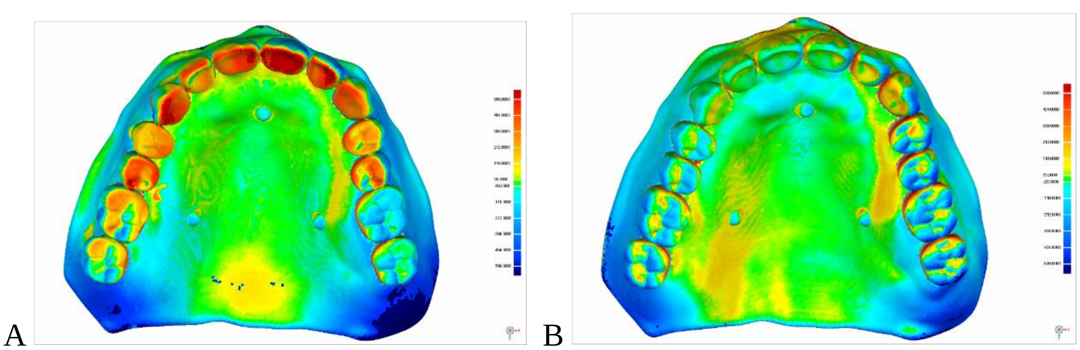


Figure 7. Qualitative evaluation of three groups. (A) CT Group specimen color map of tooth discrepancy. (B) MP Group specimen color map of tooth discrepancy.

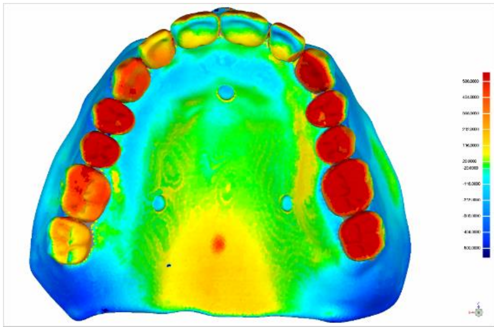
C 

Figure 7 Continued. (C) PT group specimen color map of tooth discrepancy.

Table 1 shows the tooth discrepancy values (median and interquartile range) of four different directions (buccal, lingual, mesial-distal and occlusal); The Kruskal-Wallis pairwise comparison demonstrated statistically significant differences (P<.05) among all directions of tooth discrepancy. The values (788 µm) of occlusal tooth discrepancy was significantly larger than the other three types of discrepancy (P <.05). In addition, Figure 8 demonstrates the amount and direction of denture tooth discrepancy for the specific techniques. For CT group, the teeth showed the following rankings from greatest to least tooth discrepancy: occlusal, lingual, buccal-lingual, and mesial-distal. All differences were statistically significant (P<.05) except between occlusal and buccal lingual. MP group showed the following ranking: mesial-distal, buccal-lingual, and occlusal. All differences were statistically significant (P<.05) except between mesial-distal and buccal-lingual. On the other hand, for PT group denture teeth had the following ranking from greatest to least tooth discrepancy: occlusal, buccal-lingual, and mesial-distal. All differences were statistically significant (P<.05).

Type of Discrepancy (µm)		CT	MP	PT
Occlusal	Median	260.940	-61.935	588.623
	Interquartile range	283.4	127.6	304.8
Buccal	Median	-93.268	-70.629	-35.114
	Interquartile range	142.7	163.9	326.9
Lingual	Median	258.807	143.458	334.047
	Interquartile range	137.2	94.8	255.9
Mesial	Median	12.814	146.962	293.498
	Interquartile range	141.5	116.4	163.8

Table 1. The value (median and interquartile range) of tooth discrepancy for 4 different directions.

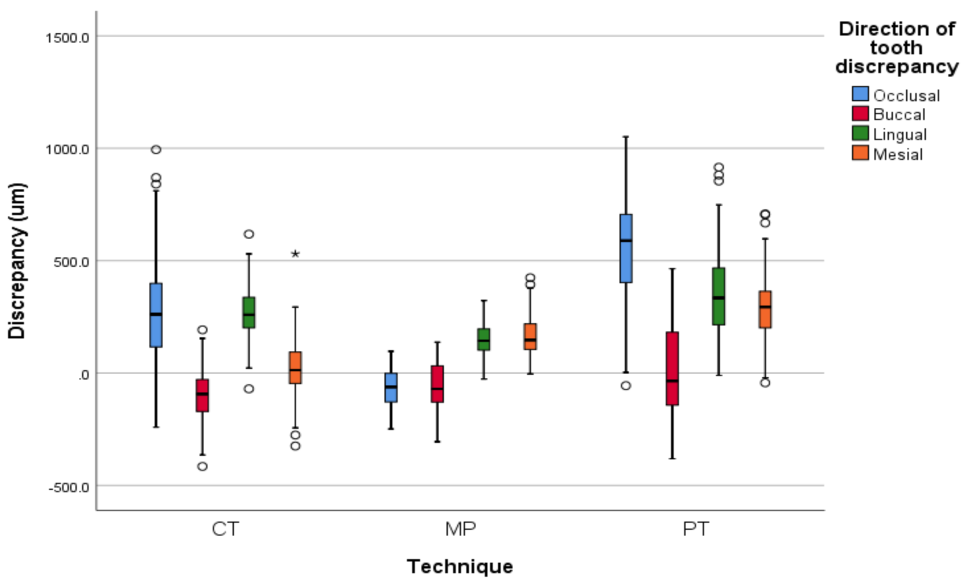


Figure 8. Results comparing processing techniques by type of denture tooth discrepancy.

Figure 9 shows the comparison of tooth discrepancy between posterior teeth and anterior teeth across all fabrication techniques. There was no significant difference between two areas (P >.05).

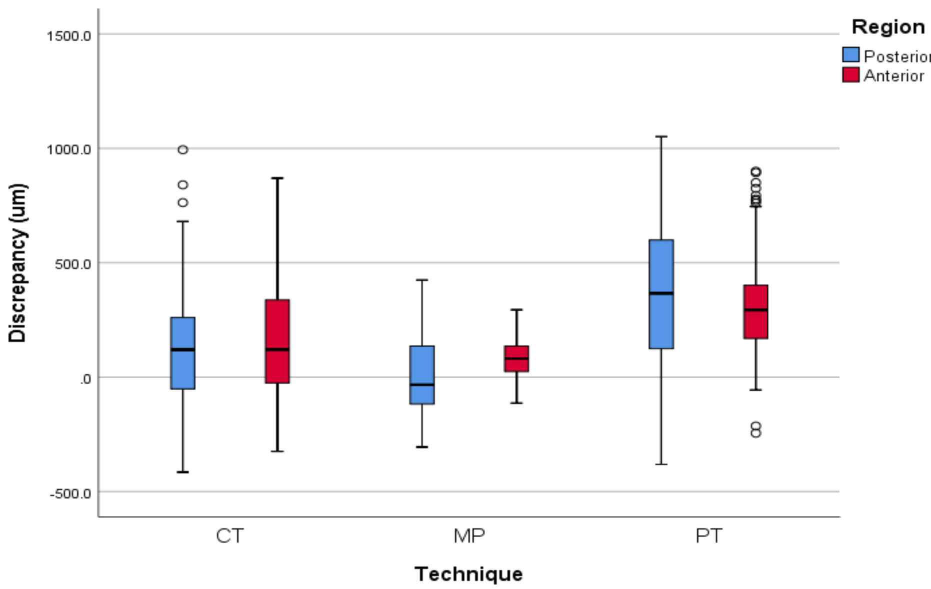


Figure 9. Results comparing processing techniques by regional discrepancies.

Figure 10 demonstrates the overall results for accuracy and reproducibility by the values of median and interquartile range, respectively. Accuracy had the following ranking from most accurate to least accurate: MP (45.3 µm), CT (119.9 µm), PT (327.8 µm). For reproducibility, the following ranking was shown from most to least reproducible by interquartile range values: MP (218.9 µm), CT (324.7 µm), PT (377.3

μm). A Kruskal-Wallis pairwise comparison of overall results demonstrated statistically significant differences ($P<.05$) among all techniques.

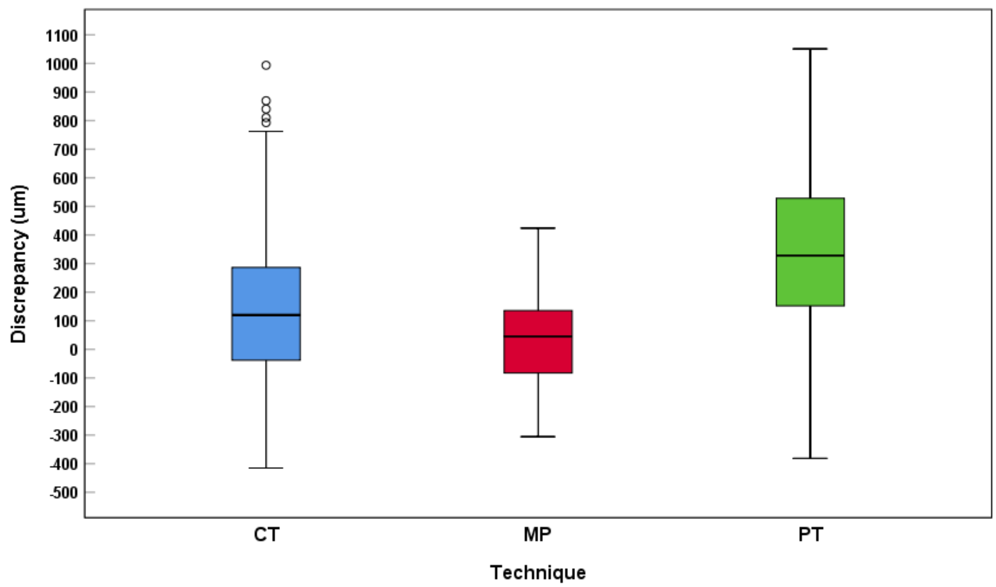


Figure 10. Overall results comparing technique.

4. DISCUSSION

This in vitro study investigated the accuracy of tooth position discrepancy values of printed dentures fabricated by three different 3D printing methods. The evaluation of accuracy and reproducibility of the printed denture tooth position revealed there were significant differences among three different groups (CT, MP, and PT). Thus, the null hypothesis was rejected. The analysis of tooth movement direction showed the occlusal direction of tooth discrepancy displayed the largest value in the CT and PT groups. In addition, the comparison between anterior and posterior area of the three groups demonstrated there was no difference between these two areas.

The monolithic print (MP) group demonstrated the best combination of accuracy and reproducibility, resulting in the lowest overall denture tooth discrepancy. A composite score of the median value and interquartile range for each of the techniques was used to rank the techniques. This composite ranking gives insights as to the performance of each technique, however it does not convey clinical nor statistical significance. Although the monolithic print technique provided the best results for accuracy and reproducibility, it did not produce zero tooth discrepancy. In practice, for all techniques tested, the clinician or technician should anticipate the necessity for some adjustment. In addition, the gingiva on 3D-printed monolithic dentures needs additional material or coloration in order to have acceptable natural esthetics, which is different from CT and PT methods. Considering overall accuracy, all discrepancy measurements in this stud ranged from - 0.415 mm in the CT group to 1.051 mm in the PT group, which is in agreement with values observed in a previous study.[11] Results of the present study demonstrate that techniques requiring assembly during processing (CT and PT) showed the greatest occlusal tooth discrepancy. This positive discrepancy means that it would cause an increase in the patient's vertical dimension of occlusion (VDO). Mahler[4] reported an increase in vertical dimension of 0.6 mm or greater depending on the pressure placed on the acrylic resin and on which type of dental stone was used in the flask or third pour of the flask. Mahler also reported that 0.25 mm of tooth discrepancy can cause a 1mm increase in vertical dimension; the present study found the CT group had a median occlusal discrepancy of +0.26 mm and the PT group had a median occlusal discrepancy of +0.59 mm. Changing the occlusal vertical dimension is one of the most highlighted concerns of many of the investigators in previous denture processing studies due to its clinical significance in successful denture therapy. Discrepancy in denture tooth position can also have a significant effect on the ease and ability of the complete denture to achieve balanced bilateral occlusion as is desired by many practitioners. The balancing of cuspal inclines in excursive movements is highly dependent upon the gross positioning of cusps and fossae with fine adjustments after processing and clinical remount to achieve bilateral balancing contacts. CAD/CAM technology aims at reducing the difficulty in establishing balancing contacts in the denture set up by using algorithms and sets of virtual teeth that will remain in a favorable position for balancing during the virtual set up, and thus the manufacturing technique must allow for true fabrication of the virtual design.

As in the similar study by Goodacre et al[12], separate buccal-lingual tooth discrepancies were evaluated to determine which direction of discrepancy was predominant, however mesial and distal tooth discrepancies were not able to be separated due to inability to make multiple direct measurements on the mesial or distal surfaces of the teeth. A larger discrepancy was demonstrated in the lingual direction compared to the buccal direction. Goodacre et al[12]observed a similar discrepancy in acrylic processing techniques and attributed this to possible tipping of the tooth instead of a bodily horizontal discrepancy. The posterior teeth did not demonstrate a greater range of discrepancy than the anterior teeth; this is in contrast to the findings of Goodacre et al[8] when evaluating acrylic processing techniques. The 3D- compare colorized maps shown in Figure 7, allow for an analysis of the direction of tooth discrepancies. 3D compare color mapping displays the directions of tooth discrepancy and can be evaluated to show the 3D discrepancy of denture teeth after processing providing a significant advantage over the previously used mechanical methods and devices.

Due to several factors, the PT group had the largest range of interquartile values, making it the least reproducible technique. The printed teeth have an additional error incorporated from the printing process which the card teeth do not. In addition, the material and surface roughness of the printed teeth allow for more friction and resistance to full seating in the denture base sockets. Lastly, the printed teeth were assembled onto the base in two large pieces with finger pressure rather than simultaneously using a jig.

Clinical and practical considerations must be considered as well when deciding on which workflow to choose. While the MP group demonstrated high accuracy and reproducibility, it is printed in one solid color and therefore would require additional steps for basic esthetics. The PT group in this study was the least accurate and varied widely in results, however they are low cost and customization is unlimited. Printed teeth currently do not offer much in the way of esthetics and are often too opaque and lack vitality. The CT group does provide considerably better esthetics due to the layering of the premanufactured teeth, but the outer layer may be entirely removed if the clinical adjustment needed is substantial. No technique is ideal and the clinician will have to make decisions on a case-by-case basis as to which aspects of the denture are most crucial for successful treatment of the patient.

A limitation of this study is the lack of a hydrating protocol prior to measurement scanning. Hydrating acrylic resin dentures for 24 hours has been recommended to reduce denture tooth discrepancy[7], however the specimens in this study were never hydrated. Most finishing techniques for printed dentures suggest applying a layer of print resin and curing rather than polishing. The printed specimens in this study were stored for 30 days prior to assembly and scanning. It is suspected that the photoactive resin may deform over time when exposed to ambient light. The low discrepancy values recorded suggest that this distortion of the printed specimens may be negligible. Other limitations include the use of a beta version of the denture planning software, the potential for premanufactured card teeth to differ from their STL design files, and the inability to use the same seating jig for the PT group. Future studies evaluating the longevity and dimensional stability of these printing materials are warranted.

5. CONCLUSIONS

Within the limitations of this in-vitro study the following conclusions may be drawn:

1. There were significant differences in denture tooth position among the three different 3D-printed denture methods (CT, MP and PT).

2. Dentures in the MP group showed lower tooth discrepancy values than those in the CT and PT groups.

3. Values of occlusal tooth position discrepancy were significantly larger than other types of movement and tended to increase the OVD.

4. There was no difference of denture tooth position discrepancy between posterior and anterior regions for all three groups.

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