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The Effect of Build Orientation on the Dimensional Accuracy of 3D-Printed Mandibular Complete Dentures Manufactured with a Multijet 3D Printer

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3D Printing; build orientation; complete removable dental prosthesis; MJP technology.

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Abstract

Purpose: To compare the dimensional accuracy of 3D-printed mandibular complete dentures with different build orientations.
Material and Methods: A mandibular complete denture was digitized as a virtual reference file. The reference file was 3D-printed at the 0°, 45°, and 90° build orientations with a MultiJet 3D printer (Projet MJP 3600 Dental, 3D systems, Rock Hill, SC). A total of 27 complete dentures were 3D-printed with 9 samples for each orientation. All printed dentures were digitized and separated into teeth, denture extension and intaglio test surfaces. The dimensional accuracy (in root mean square, RMS) was evaluated by comparing whole denture and 3 test surfaces with the reference file. One-way analysis of variance (ANOVA) and a Post-Hoc all pairs Bonferroni test were used to determine statistical differences ($\alpha = 0.05$).
Results: For the dimensional accuracy on whole denture, the 45° build orientation group showed the smallest RMS (0.170 ± 0.043 mm) than those of the 0° build orientation group (0.185 ± 0.060 mm, $p < 0.001$) and 90° build orientation group (0.183 ± 0.044 mm, $p < 0.001$). For the dimensional accuracy on the teeth, denture extension and intaglio test surfaces, the 45° build orientation group also show the smallest RMS values (0.140 ± 0.044 mm at teeth surface, 0.176 ± 0.058 mm at denture extension and 0.207 ± 0.006 mm at intaglio surface). The 0°and 90° build orientation groups had similar accuracy at the teeth (0.149 ± 0.056 mm versus 0.154 ± 0.056 mm, $p = 0.164$) and denture extension surfaces (0.200 ±0.025 mm vs 0.196 ± 0.013 mm, $p = 1.000$). However, 0° build orientation group (0.228 ± 0.010 mm) has significantly higher RMS values then those of 90° build orientation group (0.218 ± 0.057 mm) in the intaglio surface ($p = 0.032$). The teeth surfaces were most accurate in each build orientation groups, while the intaglio surfaces were least accurate.
Conclusions: The build orientation affected the dimensional accuracy of 3D-printed mandibular complete dentures, and the 45° build orientation resulted in the most accurate 3D-printed denture from a MultiJet 3D printer.

Three-dimensional printing (3D), also known as additive manufacturing, describes a process by which a product derived from a computer-aided design (CAD) is built in a layer-by-layer manner. 3D printing has introduced an era of design freedom and enabled rapid production of customized objects with complex geometries for medical use.[1,2] Dentistry is one avenue in medicine to be galvanized by 3D printing.[3] It is widely used in manufacturing fixed or removable dental prostheses and surgical templates.[4–8]

During the 3D printing process, the desired prostheses are made directly from standard tessellation language (STL) files, allowing a dental laboratory to automate the manufacturing process and decrease the need for manual labor.[9] The most common technologies employed for polymer 3D printing in dentistry are stereolithography (SLA), material jetting and material extrusion.[10,11] Multijet modeling printing (MJP), also known as PolyJet technology, uses multiple nozzles jetting one or more liquid photopolymers onto the building platform.[12–14]

SLA is considered the gold standard in 3D bio-model production and can yield resolutions up to 0.025 mm.[2,15] When compared to SLA, digital light projection (DLP) has the ability to simultaneously light-polymerize all portions of a given slice, thus significantly speeds 3D-printing times between layers.[14] Post-processing of objects manufactured from the SLA and DLP 3D printers is complicated. The printed objects need to be rinsed with ethyl alcohol to remove residual resin and incubated in the light-polymerizing unit to ensure complete polymerization. Resin remnant and incomplete polymerization may cause dimensional inaccuracy.[14] MJP can manufacture 3D objects at a high resolution (0.016 mm) and the liquid resin is immediately polymerized during the manufacturing process. The post-processing of objects manufactured from the MJP 3D printer is much less time-consuming.[16] Furthermore, MJP 3D printer is capable of utilizing multiple resin materials in a single printing task to fulfill the desired tensile strength and durability.[2]

During the 3D printing process, the polymerization shrinkage of resin materials often leads to dimensional inaccuracy.[17] Different factors can affect the accuracy of the 3D-printed objects, such as speed and intensity of polymerizing energy source, build direction and build orientation,[18–21] positioning of 3D objects on the build platform, amount, and configuration of supporting structures,[18] numbers of layers,[22] material shrinkage between layers,[20] CAD and 3D slicing software programs,[23] and post-processing procedures.[24]

3D printed one-piece complete denture has several clinical implications such as implant surgical templates, interim dentures and duplicated dentures.[6–8] It can also be used as a custom tray, or a trial prosthesis to record maxilla-mandibular relationship.[25,26] After the complete denture is digitally designed, it can be 3D-printed. However, the platform of an in-office or desktop 3D printer is relatively small and changing build orientation is an option to increase production capacity. It was reported that the build orientation affected the intaglio surface adaptation of 3D-printed complete denture [27] and dimensional accuracy of full-coverage fixed dental prostheses manufactured from SLA or DLP 3D printers.[19,28,29] However, no study has assessed the build orientation on the accuracy of 3D-printed CRDP using Multijet printers yet. The purpose of this in vitro study was to compare the dimensional accuracy of MJP-printed mandibular complete denture at different build orientations. The null hypothesis was that the build orientation had no influence on the dimensional accuracy of 3D-printed mandibular complete denture.

Materials and methods

A mandibular complete denture was digitized with a high-resolution optical surface scanner (Activity 880, Smart Optics, Bochum, Germany) and the scanned file was saved in the STL format. The STL file of the mandibular complete denture was used as the reference for the subsequent comparison of accuracy of the test STL files.[30,31] The sample size in each build orientation group (n = 9) was based on an estimate of the effect sizes at 0.25, type I error at $\alpha = 0.05$ and type II error at $\beta = 0.80$.[24] A total of 27 specimens were 3D-printed with a hybrid light-polymerizing resin (VisJet M3 crytal, 3D systems, Rock Hill, SC) using a Multijet printer (Projet MJP 3600 Dental, 3D systems, Rock Hill, SC) (Fig 1). The STL file of reference complete denture was placed in a slicing software (3D Sprint Software, 3D systems, Rock Hill, SC) at 0°, 45°, and 90° build orientations (n = 9) (Fig 2). The build orientation was defined as the angle between the occlusal plane of the complete denture and the build platform. The 3D printing resolution of the selected printer at the x, y, and z axes is 750 × 750 × 1600 dots per inch (DPI). The layer thickness for 3D printing is 16 μm.

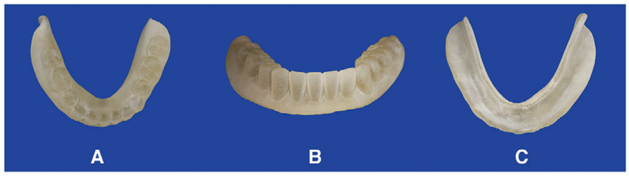

Figure 1 Mandibular complete denture manufactured with Multijet 3D printer. (A) Occlusal view. (B) Frontal view (C) Intaglio view.

When the printing process was completed, the 3D-printed complete dentures were carefully removed from the build platform and placed on a metal basket inside an oven at 158°C for 30 minutes to melt away the supporting wax material. The 3D-printed specimens were then immersed in a mineral water bath (EZ Rinse-C, 3D Systems, Rock Hill, SC) at 65°C for 30 minutes. The 3D-printed complete dentures were rinsed and dried.[8] With the 7-days post-production time frame, all 27 printed dentures were lightly coated with anti-glare spray (Super check UD-ST, Marktec, Tokyo, Japan) and then digitized with the same optical surface scanner (Activity 880, Smart Optics, Bochum, Germany) and the corresponding software (Activity version 2.6.0; Smart Optics). The occlusal and intaglio portions of the 3D-printed complete dentures were scanned separately and two scans were merged in a 3D scanning software program (Geomagic Wrap 2015 software, 3D systems). Initial manual registration with 3 common points between occlusal and intaglio scans was completed. Global registration was then applied in the same 3D scanning software program to achieve accurate registration between occlusal and intaglio scans. The occlusal and intaglio scans were subsequently merged after removing overlapping areas. The merged files were saved in the STL file format and labeled accordingly for the ease of future identification.

The STL files of reference denture and all the test dentures were imported into a 3D inspection software (Geomagic Wrap 2015 software, 3D systems, Rock Hill, SC). Each test complete denture was first aligned manually with the reference denture by selecting 3 corresponding matching points, one point in left incisal edge of right central incisor, one point in central fovea of left first molar, and one point in gingiva zenith of right second molar. These three matching points were widely distributed across the anterior-posterior and right-left sides of complete denture. The wide distribution of matching points facilitated initial manual alignment. The best-fit alignment function in the software program was used to optimize and finalize the superimposition. Furthermore, all STL files of complete dentures were separated into identical teeth, denture extension and intaglio surfaces (Fig 3). The three surfaces of

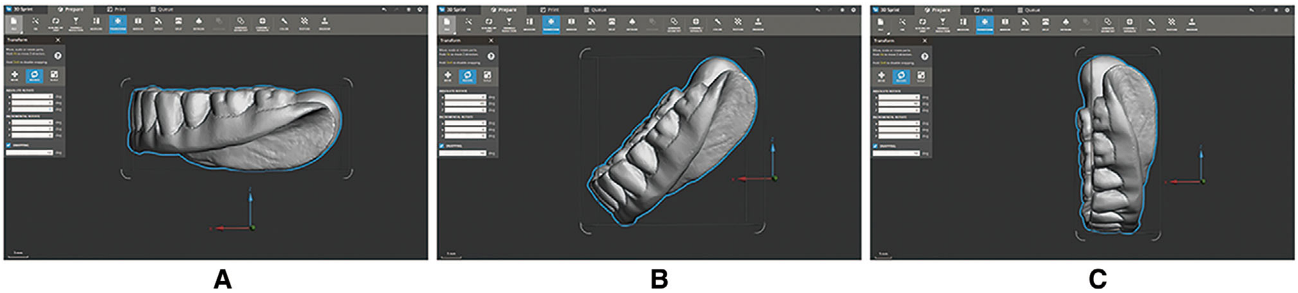

Figure 2 Printing configuration of the mandibular complete denture in the software in 3 different build orientations. (A) 0 degrees. (B) 45 degrees. (C) 90 degrees.

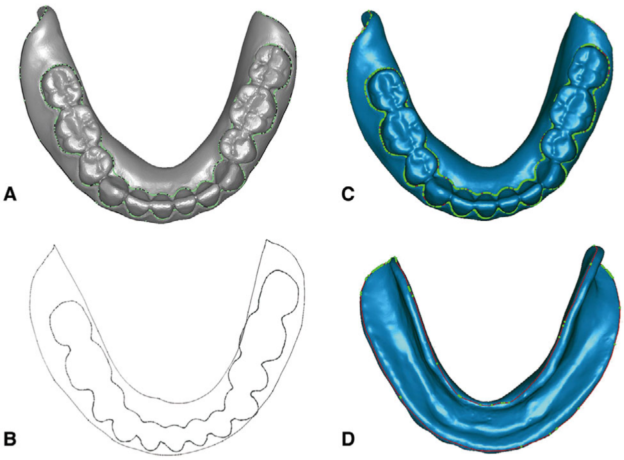

Figure 3 Graphical component of curves to separate complete denture into three surfaces. (A) Draw two curves on reference model. (B) Two curves. (C) Occlusal view of test cast trim with curves. (D) Intaglio view of test cast trim with curves.

the reference and test dentures were exported and saved in STL format, resulting in 3 reference files and 81 test files.

All test STL files of the printed denture were superimposed to the corresponding reference STL files using automatic best-fit alignment in a surface matching software (Geomagic Control X software, 3D Systems, Rock Hill, SC). Dimensional differences between test and the corresponding reference STL files were computed in the root mean square (RMS, measured in mm, absolute value). The RMS values were used to represent overall accuracy, estimating the congruency of 2 superimposed virtual files.[32,33] A color map was produced to show the 3D differences between a test surface and the reference surface.[34] All dentures were scanned and analyzed by the same trained operator.

To determine differences in accuracy (RMS, measured in mm) among the 3 build orientation groups, comparison was made for the whole denture and across teeth, denture extension and intaglio surfaces. For each build orientation, accuracy comparison was also performed among different surfaces. One-way analysis of variance (ANOVA) and post-hoc Bonferroni Test were used to determine differences in dimensional accuracy among the groups with three surfaces were compared separately. Statistical software (SPSS version 24, IBM SPSS Inc, Armonk, NY) was used for all statistical analysis ($\alpha = 0.05$).

Results

Accuracy of the whole denture and across three surfaces are shown in Table 1. The 45° build orientation group resulted in smallest overall RMS of all test groups (0.170 ± 0.043 mm) and showed significant difference from 0° group (0.185 ± 0.060 mm, $p < 0.001$) and 90°group (0.183 ± 0.044 mm, $p < 0.001$), while the latter 2 groups had similar results ($p = 0.753$). The 45° build orientation group resulted in smallest RMS value of all three tested surfaces (0.140 ± 0.044 mm in teeth area, 0.176 ± 0.058 mm in denture extension area and 0.207 ± 0.006 mm in intaglio area, respectively), which showed significant difference from the other groups. The 0° and 90° group had similar accuracy in both the teeth (0.149 ± 0.056 mm vs 0.154 ± 0.056 mm, $p = 0.164$) and denture extension (0.200 ± 0.025 mm vs 0.196 ± 0.013 mm, $p = 1.000$) surfaces, however showed significant difference in the intaglio surfaces (0.228 ± 0.010 mm vs 0.218 ± 0.057 mm, $p = 0.032$). The teeth surfaces were most accurate in each build orientation group, while the intaglio surfaces were least accurate.

Color maps of the surface matching differences for the 3 build orientation groups in the teeth, denture extension and intaglio surfaces are shown in Fig 4. Most of the areas were green in color, indicating that most surface matchings were within 0.3 mm in dimensional difference. Blue areas (negative discrepancies) indicate smaller test denture surfaces when compared with the corresponding reference denture surfaces. Yellow and red areas (positive discrepancies) indicated larger test denture surfaces when compared with the corresponding reference denture surfaces. Of the 3 build orientation groups, 45° group showed most uniform surface matching and had largest green area in all 3 test surfaces. The blue, yellow and red areas in the color map was unevenly distributed and located.

Discussion

The statistical analysis rejected the null hypothesis, confirming that build orientation affected the overall accuracy in all

Table 1 Mean (±SD) RMS values for whole denture, teeth, denture extension, and intaglio surfaces of three building orientations

	Whole denture mm± SD	Teeth mm ± SD	Denture extension mm ± SD	Intaglio mm ± SD
0°	0.185 ± 0.060^{a}	$0.149 \pm 0.056^{a,*}$	$0.200 \pm 0.025^{a,**}$	$0.228 \pm 0.010^{a,***}$
45°	0.170 ± 0.043^{b}	$0.140 \pm 0.044^{b,*}$	$0.176 \pm 0.058^{b,**}$	$0.207 \pm 0.006^{b,***}$
90°	0.183 ± 0.044^{a}	$0.154 \pm 0.056^{a,*}$	$0.196 \pm 0.013^{a,**}$	$0.218 \pm 0.057^{c,***}$

SD, standard deviation; RMS, root mean square; Accuracy with same denoted letter (a, b, c) in the same column is not statistically different at P = 0.05. Accuracy with the same denoted symbol (*, **, ***) in the same row is not statistically different at P = 0.05.

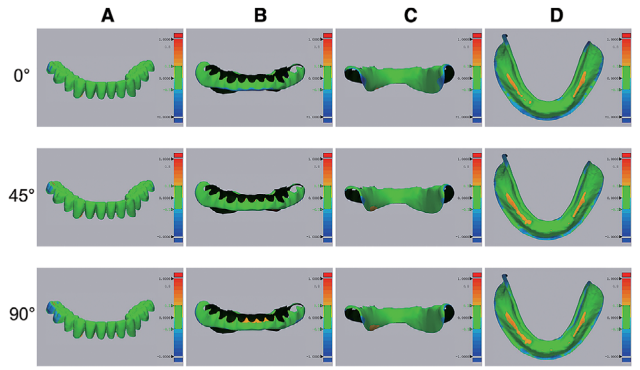

Figure 4 Representative surface-matching color maps from 3 build orientations (0°, 45°, 90°). Green areas indicate dimensional difference within 0.03mm, blue areas indicate negative discrepancies, yellow and red areas indicate positive discrepancies. (A) Teeth surface. (B) Denture extension surface front view. (C) Denture extension surface back view. (D) Intaglio surface.

test surfaces. The 45° build orientation group produced the most accurate 3D-printed complete dentures. The teeth surfaces were most accurate in all build orientation groups, while the intaglio surfaces were least accurate.

The build orientation affected the overall accuracy in a variety of ways. First, the build orientation related to layers number, given a constant thickness of each layer, the reference dentures with different build orientations were sliced into different number of layers in the supporting software,[22] for instance, the 90° denture had the greatest number of layers in the present study. More layers increased dimensional inaccuracy of the 3D-printed complete dentures. Second, the build orientation also affected the self-supporting geometry of the object.[28] In the 3D printing process, a small amount of an object can be 3D-printed without supporting structures when the previously polymerized material can withstand overhang structure while it's polyermizing.[22] The 45° build orientation resulted in best accuracy which may be attributed to its most favorable self-supporting geometry, and its support for the overhang structure during the 3D printing process. This finding was consistent with previous studies, showing that 45° (135°) build angle offers better results when 3D printing bar-like samples with an SLA printer,[24] or fixed dental prostheses[28] and complete denture bases[27] with DLP printers.

Third, the supporting structure should be generated for all the areas that require external support to withstand overhang.[22] Insufficient support may lead to distortion or inaccuracy of the 3D-printed objects. The SLA and DLP printers use the same material as the 3D-printed object to build the supporting structures. Thus, the supporting structures should be designed for the ease of removal. The connections between supporting structures and 3D-printed object should be as small as possible to eliminate residual notches after the removal of supporting structures.[24] Without supporting structures, printing objects directly on the building platform could increase overall thickness, especially in thin areas and cause compression and protrusion of the initial layer adjacent to the build platform due to additional laser exposure and should be avoided.[24] The MJP printer used supporting structures with wax material, and the wax material can be easily removed by using a heating oven and warm water wash.[14,35] One advantage of an MJP printer is that the supporting structures can be melted and cleaned without damaging the surface on a 3D-printed object.[34]

Significant accuracy difference was found among the teeth, denture extension and intaglio surfaces. In the clinical scenario, accurate teeth duplication can facilitate a precise interocclusal record. The accurate intaglio surface is related to the better tissue adaptation.[27] The build platforms in the SLA and DLP printers situates at the top of the printers, and the printed objects are hung upside down on the build platforms in the printing process. Unlike SLA and DLP printers, the MJP printer's build platform is situated at the bottom of the printer, and it manufactures an object on top of the platform. Considering the geometry of the denture and the build orientations used in the study, the teeth part had better support than the denture base (divided into denture extension and intaglio surfaces) in the printing process. This may explain the finding that the teeth surfaces were most accurate in all build orientation groups.

Color maps from the surface matching software program can show the distribution of positive or negative deviation areas. In this study, areas in blue color were mainly located at buccal aspects of molars and denture extension, and posterior mandibular hyoid fossa area. Most of the yellow areas were at the crest of ridge in premolar and molar regions. The areas in yellow color should be relieved to get favorable soft tissue adaptation with the residual ridge. Although statistically significant differences were found among groups, it is noteworthy that the absolute values of all differences were extremely small and may not create any significant effects in clinical scenarios.

There were several limitations of this study. The 3D deviations of all test dentures were affected by the combined accuracy of 3D printing and surface scanning. The scanning accuracy of surface scanner (Activity 880, Smart Optics, Bochum, Germany) used in this study is assumed to be 0.010 mm by the manufacturer. The scanning accuracy may have small influences on the accuracy measurement of 3D-printed compete dentures (RMS 0.179 ± 0.049 mm). Future in vitro study may consider industrial scanners with higher accuracy to minimize the influence from the surface scanning. Another limitation of this study was only one MJP 3D printer and one resin material combination were evaluated. If the denture base and dentition were printed separately,[7] the results may not be relevant to this study. Therefore, the conclusions drawn based on this study may not be generalized for other printers and materials. Since SLA, DLP and MJP printing technologies have been widely used, further investigation may include more 3D printers, orientation groups and prostheses types.

Conclusions

Mandibular complete dentures 3D-printed at 45° build orientation show higher accuracy than those manufactured at 0° and 90° build orientations in the teeth, denture extension and intaglio surfaces. In each build orientation group, the teeth surfaces are most accurate, followed by the denture extension surfaces. The intaglio surfaces are least accurate. The MJP 3D printer and resin material combinations produce accurate mandibular complete dentures. The intaglio surface at the crest of ridge may need relief to facilitate soft tissue adaptation.

Acknowledgments

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