The Effect of Print Angulation on the Surface Roughness of 3D-Printed Models

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Abstract

Additive manufacturing processes are increasingly being used in dentistry. The underlying process is the polymerization or fusion of material layer by layer to create layer lines on the final printed surface. How print orientation affects these layer lines is unclear. The primary objective of this research was to measure and compare the surface waviness and surface roughness of maxillary models fabricated using a variety of 3D printers and resin types, and to evaluate the effect of different print angulations. The same STL file was used to manufacture 48 models using a variety of resins and printers at 0 degrees, 30 degrees (with base supports), and 70 degrees ("vertical" without supports) to the build plate. Six replications with each angulation were printed. All samples were optically scanned with a laser profilometer and compared. The results indicated that print angulation can significantly affect the surface roughness of 3D-printed objects, but the results seemed to be specific to the resin/printer products and angles. The authors concluded that surface waviness values should be considered whenever surface smoothness is evaluated.

While dentistry has had a long association with subtractive manufacturing such as milling, additive manufacturing (AM) is a relatively new process that offers capabilities that cannot be done with subtractive manufacturing.[1] Along with lower cost and increased efficiency, the opportunity for new possibilities is perhaps why AM is being utilized in dentistry at an increasing rate and has penetrated nearly all aspects of patient care. The use of 3-dimensional (3D) printing is becoming increasingly common in the fabrication of both complete and partial denture prosthetics, surgical guides, models, dies, clear aligner bases, occlusal splints, indirect bonding trays, burnout patterns, provisional prosthetics, and much more.[1-3] In all digital fabrication processes, the object to be fabricated is placed into a Cartesian coordinate system consisting of closed, triangular spaces, ie, STL (standard triangulation language) file format. The 3D object is deconstructed into 2-dimensional file "slices" that are sequentially produced using a layer-by-layer strategy.

Fused deposition modeling (FDM), also known as fused filament fabrication, is an extrusion process of layering successive heights of warmed filament that fuse to each other as they are deposited and form the final product when cooled.[4] Various active polymerization processes are also used in 3D printing. Processes that use a bath of unpolymerized resin, ie, a stereolithography apparatus (SLA), employ an ultraviolet (UV)-based laser to trace out the features of each slice; digital light projection (DLP) technology projects an image of an entire slide onto the bottom of the resin bath all at once; and polyjet photopolymerization utilizes printing technology much like an inkjet printer.[4] Each of these technologies achieves slightly different resolution and accuracy, which can be important with regard to how well the printer produces dental appliances. Resolution is the finest or smallest feature of an object that a 3D printer generates. (A printer both *produces* a designed object or *reproduces* an object that has previously been scanned.) Resolution is specific to each technology and printer and is measured along X, Y, and Z axes and in micrometers (μm) or dots per inch (DPI). The Z axis usually corresponds to the layer thickness. The X-Y resolution is typically determined by the nozzle diameter (in FDM), laser dot size (in SLA), or pixel size (in liquid crystal display [LCD] and DLP).[3,5] All of these variances can affect print surface roughness (Sa).

One often-overlooked factor that also can impact surface roughness is print angulation. When a user places a 3D model into the print software to prepare for AM, three common orientations typically are used: flat horizontal (ie, 0 degrees), 30-degree angulation, and 70-degree angulation relative to the build platform. These different angulations can affect the dimensional accuracy, surface smoothness, and detail reproduction. Surface roughness is determined by averaging roughness over a predefined area, not accounting for object form. In contrast, waviness, a characteristic that should not be overlooked, considers the object form roughness and is detectable without the need for magnification. Surface roughness and waviness both can be important factors depending on the clinical application of the 3D-printed device. For example, while surface roughness or waviness may not affect the clinical performance of 3D-printed clear aligner bases and surgical guides, these factors may impact the amount of finishing work needed for a 3D-printed denture or digital smile design try-in.[6,7] Additionally, a recent study found that printing orientation significantly influenced the roughness of denture base resins and, subsequently, their response to *Candida albicans*.[7]

Objectives

The primary aim of this research was to measure and compare the surface waviness and surface roughness of 3D maxillary models fabricated with a variety of 3D printers and resin types used in the dental industry to evaluate the effect of different print angulations. The research hypothesis was that models printed at 70-degree angulation would demonstrate significantly rougher surfaces (both in waviness and surface roughness) than models printed horizontally or at 30-degree angulation.

Materials and Methods

Master Model Fabrication

A random maxillary cast was selected and digitally scanned using a desktop scanner (Medit T500, Medit, medit.com). The model was modified to include five pillars distributed across the arch to ensure ease of measurements; also, a base was constructed to help standardize the model positioning across all of the different 3D printers, creating a 30-degree bevel in the posterior area to allow for vertical and angulated surface selection to ensure proper model orientation on the build plate.

3D Reproductions of the Master Model

The same STL file was used to manufacture a total of 48 models using a variety of resins and printers at 0 degrees, 30 degrees (with base supports), and 70 degrees ("vertical" without supports) to the build plate (Figure 1). Six replications were made for each angulation. All models were printed at a 50-µm Z-axis resolution in all 3D printers except for one (Objet Eden260V, Stratasys, stratasys.com) that was set to 28 µm, the printer's maximum µm layer thickness. The post-curing process for DLP and SLA printers was standardized and consisted of two 15-minute isopropyl alcohol washes at a 95% concentration in two separate containers, followed by a 15-minute UV-light post-curing exposure (Table 1).

Optical Scans of Reproduced Models

All samples were optically scanned with a laser profilometer (ST400, Nanovea Inc., nanovea.com) using a custom-made positioning jig to ensure consistency of model orientation in a reproducible, upright position. The same 5 mm x 9 mm area of the facial surface of tooth No. 10 was selected as the scanned area (Figure 2). Software (TalyMap® Gold [V.7.4.8114], Taylor Hobson, taylor-hobson.com) was used to determine surface roughness (form removed) or waviness (with form) on the same area of each tooth. The sequence of steps was as follows: extract area, fill in non-measured points, remove outliers, run 80-µm standard filter. Surface area waviness was then exported, and surface roughness in µm was then exported after the surface form was subtracted.

Statistical Analyses

All values were exported to a spreadsheet. Data were analyzed using a two-factor (resin/printer combination and angulation) analysis of variance (ANOVA). Because of the presence of significant interaction terms, follow-up single-factor ANOVAs were performed within each resin/printer combination among angulations. Pairwise, post-hoc means comparisons were made using Tukey's range test, where appropriate. All statistical testing was performed using a preset alpha 0.05.

Results

Surface Roughness (Sa) Analysis

Sa values ranged from a low of less than 1 µm (using the SLA printer) to a high of almost 3 µm (with the FDM printer) (Figure 3). The two-factor ANOVA indicated strong, significant effects for both resin/printer combination and the interaction term with angulation ($P < .001$) but no significant influence of angulation ($P = .149$). Because of the significant interaction of terms, global statements regarding the overall effect of print angulation and combination of resin/printer cannot be made.

For Sa, five of the eight resin/printer combinations demonstrated a significant influence of angulation, with no general trends observed. However, within each resin/printer combination, printing at the highest angulation resulted in either the significantly lowest Sa value, or provided a Sa value not significantly different from those printed at lower angulations. The effect of resin/printer combination was interesting. When used with the MoonRay S100 3D printer (SprintRay, sprintray.com), the SprintRay die and model gray resin demonstrated significantly lower Sa values when printed at the highest angulation (70 degrees); but when a different resin (ie, SprintRay die and model tan resin) was used on the same printer, there was no significant effect of angulation. Comparing the effect of the printer on that same resin, the newer SprintRay Pro printer showed a trend of higher Sa value with lower print angulation.

Surface Waviness Analysis

When including the form in the roughness calculation, the average Sa values were much greater than when the form was eliminated. The lowest waviness value seen was near 33 µm, while the highest noted was close to 75 µm (Figure 4). The two-factor ANOVA also indicated a significant influence of the resin/printer combination and that parameter interacting with angulation (each with $P < .001$). Angulation by itself did not provide a significant influence on surface waviness ($P = .11$).

As with Sa analysis, there did not seem to be an overall trend of waviness with print angulation among the different resin/printer combinations. Six of the eight resin/printer combinations indicated that their waviness values were not significantly affected by print angulation. Of the two combinations indicating that print angulation had a significant effect, the models printed at the highest angulation (70 degrees) demonstrated higher waviness values. Interestingly, the influence of DLP printer and resin showed a different trend than that seen in the Sa analysis. When using the MoonRay S100 printer with the SprintRay die and model gray resin, although not significantly different, there was a trend for increased surface waviness with lower print angulations, also with high degrees of variation. However, models printed using a different resin (SprintRay die and model tan resin) on the same printer indicated just the opposite: higher waviness with higher print angulation. Greatly different results were seen when printing models with the SprintRay die and model tan resin on the older MoonRay S100 printer than on the newer SprintRay Pro model. When using the newer printer, waviness values were much less than on the older printer and were also not affected by print angulation, but angulation did affect this resin on the MoonRay S100 printer.

Discussion

The research hypothesis-that use of the highest print angulation would result in rougher surfaces (higher surface roughness and waviness values)-was not universally observed. For surface roughness analysis, models printed using the highest angulation provided either the lowest Sa values, or their values were not significantly different from those printed at lower angles, as confirmed in the literature.[8]

For surface waviness, in both of the instances where the resin/printer combinations demonstrated a significant difference among print angulations, the highest angulation demonstrated the highest roughness value. In all other cases, the waviness values of models printed at high angles were not significantly different from those printed at lower ones.

A noteworthy aspect of this research is that the evaluation of surface roughness was done both with the object form (waviness) and without it (conventional Sa value). Initially, the authors used only Sa values for roughness analysis. They noted, however, that although they could see obvious roughness, the Sa values were below 5 µm. For such a low Sa value, one would expect almost a mirror-smooth surface, yet models clearly and visibly demonstrated roughness. Upon altering the analysis parameters to include the surface form, thereby incorporating a staircase effect or undulations provided by the layer-by-layer surface deposition, a much more appropriate value of surface roughness was seen in the form of waviness. Thus, the authors would advise that future research of 3D-printed parts utilize surface waviness, and not merely Sa, because the true value of roughness is not obtained using only Sa parameters. Other authors have reported the same macroscopic staircase or wavy effect occurring along surfaces of printed areas.[8,9]

Overall findings have indicated that the print angulation of an object can significantly affect its surface roughness, especially when waviness is evaluated. Arnold et al found that the surface quality of 3D-printed models using SLA technology is dependent on the direction and inclination of the models.[10] The main limitations in most studies on this topic are that they did not include waviness or they lacked different 3D printing technologies in their comparisons. Contrastingly, the present study focused on validating previous findings using various 3D printing technologies used in dentistry and found similar results.

Surface roughness is an important consideration, especially when esthetic wax-up models or prototypes are being printed. Excessive surface roughness could impact the relationship between the natural texture of a digital tooth in a digital tooth library and the printed model. Although in the present study all models except for one were printed at 50-μm Z-layer resolution, it is unclear if changing the Z-axis resolution or using different post-curing methods would provide different results. According to Cheng et al the inclination combined with reduced layer thickness can result in significantly smoother surfaces[8]; in this case 50 μm was chosen as a standard resolution but different results may be obtained with different Z-layer parameters. Furthermore, the results proved to be printer- and resin-specific. Similar studies have shown that 3D-printing accuracy could be affected by factors such as the type of printer and layer thickness.[11] Thus, changing resins or modifying resin formulations within the same printer may result in different surface waviness values. Manufacturers should conduct further research to develop resin formulations that can garner improved results over what is currently being achieved.

Conclusions

Within the limitations of the current study, it may be concluded that print angulation can significantly affect the surface roughness parameters of 3D-printed objects, but results seem to be product-specific to resin/printer and angle-specific. Also, surface waviness values should be considered when evaluating surface smoothness.

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References

1. Dawood A, Marti BM, Sauret-Jackson V, Darwood A. 3D printing in dentistry. *Br Dent J*. 2015;219(11):521-529.

2. Hazeveld A, Huddleston Slater JJ, Ren Y. Accuracy and reproducibility of dental replica models reconstructed by different rapid prototyping techniques. *Am J Orthod Dentofacial Orthop*. 2014;145(1):108-115.

3. Revilla-León M, Özcan M. Additive manufacturing technologies used for processing polymers: current status and potential application in prosthetic dentistry. *J Prosthodont*. 2019;28(2):146-158.

4. Azari A, Nikzad S. The evolution of rapid prototyping in dentistry: a review. *Rapid Prototyp J*. 2009;15(3):216-225.

5. Jockusch J, Özcan M. Additive manufacturing of dental polymers: an overview on processes, materials and applications. *Dent Mater J*. 2020;39(3):345-354.

6. Dalal N, Ammoun R, Abdulmajeed AA, et al. Intaglio surface dimension and guide tube deviations of implant surgical guides influenced by printing layer thickness and angulation setting. *J Prosthodont*. 2020;29(2):161-165.

7. 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*. 2020;124(4):468-475.

8. Cheng W, Fuh JYH, Nee AYC, et al. Multi-objective optimization of part-building orientation in stereolithography. *Rapid Prototyp J*. 1995;1(4):12-23.

9. Byun HS, Lee KH. Determination of the optimal build direction for different rapid prototyping process using multi-criterion decision making. *Robot Comput Integr Manuf*. 2006;22(1):69-80.

10. Arnold C, Monsees D, Hey J, Schweyen R. Surface quality of 3D-printed models as a function of various printing parameters. *Materials (Basel)*. 2019;12(12):1970.

11. Favero CS, English JD, Cozad BE, et al. Effect of print layer height and printer type on the accuracy of 3-dimensional printed orthodontic models. *Am J Orthod Dentofacial Orthop*. 2017;152(4):557-565.