EFFECT OF BUILD ANGLE AND PRINT LAYER THICKNESS ON CLINICAL ACCURACY OF 3D-PRINTED ORTHODONTIC MODELS

A THESIS IN
Oral and Craniofacial Sciences

Presented to the Faculty of the University
Of Missouri-Kansas City in partial fulfillment of
the requirements for the degree

MASTER OF SCIENCE

by
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Kansas City, Missouri
2024

EFFECT OF BUILD ANGLE AND PRINT LAYER THICKNESS ON CLINICAL ACCURACY OF 3D-PRINTED ORTHODONTIC MODELS

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ABSTRACT

This study investigated how variations in print layer thickness and build angle impact the accuracy of orthodontic models produced using a digital light processing (DLP) 3D printer. Orthodontic models were generated from a digital master model derived from an ideal maxillary typodont scan. The study tested six different configurations: 100 µm-0°, 100 µm-70°, 100 µm-90°, 170 µm-0°, 170 µm-70°, and 170 µm-90°.

Following printing, the experimental models underwent scanning, and the scan data were analyzed against the digital master model using 3D superimposition software. A ±0.25 mm range was established as clinically acceptable deviation between the digital master and experimental models.

The findings indicate that both build angle and print layer thickness influence the final accuracy of the printed models. In this study, models printed with a 170 µm layer thickness demonstrated slightly greater accuracy across all build angles compared to those printed with 100 µm thickness. These results suggest that choosing the appropriate print layer thickness can offer flexibility in achieving accurate clinical outcomes.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Dentistry, have examined a thesis titled “Effect of Build Angle and Print Layer Thickness on Clinical Accuracy of 3D-Printed Orthodontic Models”, presented by Brandon Knapp, candidate for the Master of Science Degree in Oral and Craniofacial Sciences, and certify that in their opinion it is worthy of acceptance.

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ACKNOWLEDGEMENTS

I would like to give thanks and express my sincere appreciation to:

Dr. Stefan Lohfeld for his invaluable assistance with obtaining technology for this experiment as well as his guidance in writing.

Dr. Mary Walker for her expert help in formatting and refining the thesis.

Dr. Yong Wang for his thorough review of the thesis.

Marie Thompson for her meticulous help with thesis formatting.

Jessica Moniz for her organization and administrative skills.

My wife, Genelyn Knapp, for her unwavering support throughout residency.

CHAPTER 1

INTRODUCTION

The rapidly advancing field of additive manufacturing, more commonly known as three-dimensional or “3D” printing, is revolutionizing the landscape of fabrication and production. Industries that are currently using this technology include pharmaceuticals, transportation, fashion, textiles, and medicine (Chadha et al. 2022). Dentistry has also embraced 3D printing and applications have been developed in oral surgery, periodontics, endodontics, prosthodontics, restorative dentistry, and orthodontics (Dawood et al. 2015).

The 3D printing process begins with a 3D digital model obtained using a desktop or intraoral 3D scanner. The 3D scanner creates a digital model by using optical light and computer vision to register the real-world object as a cloud of mathematically plotted points or point cloud. These points are related to one another via a polygonal mesh to generate a digital rendering of the real-world object. This digital model is then formatted into one of several file types with the most common being the standard tessellation language file type (STL) (Farahani et al. 2017).

This is where additive manufacturing, or 3D printing, differs from subtractive manufacturing or “milling”. Instead of removing large amounts of material from a stock block to create the desired shape, 3D printing directly fabricates the desired shape layer by layer (Oberoi et al. 2018). This reduces the amount of waste produced by the fabrication process as well as improves accuracy since the details are not limited by the size of the bur used in the milling process (Martorelli et al. 2013; Shim et al. 2020).

Due to the broad scope of application, current high level of interest, and decreasing cost, 3D printing technology is continually advancing with updates that are touted to improve efficiency and accuracy. As these advancements come to market, research is required to continually validate the accuracy and application for each new iteration of updated capabilities.

3D Printing in Dentistry

Additive manufacturing, or 3D printing, application in dentistry has increased in popularity throughout the last several years. As this technology becomes increasingly accessible, dental practitioners are discovering new uses for their own in-office 3D printers. Dawood et al. (2015) has described how oral surgery procedures have been enhanced by 3D-printed surgical guides for implant placement, how 3D-printed models are used to better understand complex boney anatomy in patients with cleft palate, and how they can aid in treatment planning of restorative implants. Further surgical applications include 3D-printed mandibular models used to aid in pre-operative design and adaptation of osteosynthesis plates in mandibular surgical cases (Dawood et al. 2015).

Oberoi et al. describe how both the specialties of endodontics and periodontics have improved with the implementation of 3D printing. Endodontics has found uses in the fabrication of guides for endodontic access cavity preparations and apicoectomies. There are even case reports of endodontists using 3D-printed tooth models complete with internal anatomy as a guide in complex endodontic cases. Periodontics has primarily focused on 3D printing’s use in periodontal tissue regenerative procedures and esthetic gingival surgeries (Oberoi et al. 2018).

Fixed and removable prosthodontic procedures have also been influenced by this technology. 3D-printed provisional crowns have been shown to overcome some of the deficiencies of traditional directly fabricated acrylic based provisional crowns such as polymerization shrinkage and marginal discrepancies (Ryu et al. 2020). These 3D-printed provisional crowns have also shown to have improved microhardness and intaglio fit when compared to traditional temporary crowns (Digholkar et al. 2016; Alharbi et al. 2018). Some dental laboratories have embraced 3D technology and are using selective laser sintering to fabricate metal frameworks for partial dentures and metal copings for porcelain fused to metal crowns in addition to directly printing resin denture bases (Dawood et al. 2015; Shim et al. 2020). Overall, 3D printing has permanently enhanced the process of restoring and improving oral health, function, and esthetics.

3D Printing in Orthodontics

The specialty of orthodontics has been shaped by the growing influence of 3D printing technology and has found applications for its use in the fabrication of orthodontic retainers, appliances such as palatal expanders, and indirect bonding guides (Dawood et al. 2015). Oberoi et al. report that orthodontists are printing occlusal splints for those suffering from temporomandibular joint dysfunction and even exploring directly printed orthodontic brackets. Predominately, orthodontics uses 3D printing technology to directly print dental models to aid in the fabrication of clear aligners (Oberoi et al. 2018).

Clear aligner orthodontic therapy begins by obtaining a 3D scan of a patient's dentition to create a digital model. An orthodontist will then digitally reposition the teeth to achieve improved esthetics, occlusion, and function. The tooth movements between the "start" dental positions and the "final" dental positions are then broken up into defined stages and the models are 3D printed. These models are used to produce a series of thermoformed clear aligners that are worn to progressively move the teeth into their desired locations (figure 1) (Dawood et al. 2015). The future may hold the possibility to directly 3D print the clear aligners, which would eliminate the need for 3D-printed models and clear aligner fabrication. However, it has been shown that traditionally fabricated thermoform aligners deviate less from the original model when compared to directly 3D-printed clear aligners (Cole et al. 2019).

Figure 1. 3D-printed dental model and thermoformed clear aligner.

Traditionally, 3D-printed dental models and thermoformed clear aligners were produced on a large scale in commercial settings by large third-party companies. Some of the drawbacks associated with using these third-party companies include increased cost to both the patient and clinician, increased time required to communicate with the third-party company about treatment plan modifications, and shipping time to the clinic. Recently, the increased accessibility to 3D printing technology has influenced many private orthodontic clinics from using third-party companies to completely fabricating clear aligners in-house. This change in the fabrication process from large third-party companies to in-house production has the potential to introduce increased variation. This variation may have detrimental effects on the accuracy of the 3D-printed models and therefore will negatively affect the fit and efficacy of the clear aligners (Camardella et al. 2017). A thorough evaluation of factors that affect clinical accuracy is necessary for a better understanding of how to appropriately use this technology in patient care.

Clinical Accuracy of 3D-printed Models

Incorporating digital models for use in 3D printing offers many benefits to the modern orthodontic practice. For example, thousands of patient records can be saved and organized on a small hard drive, 3D scans can be sent directly to dental labs for appliance fabrication, and models can be instantly accessed and printed as needed. A position that is gaining support is that digital models should become the new golden standard in modern orthodontics (Rossini et al. 2016). These conveniences do not, however, diminish the need for clinically accurate records; therefore, it is appropriate to evaluate the accuracy of this new format of dental models. Fortunately, the scanning technology used to obtain digital models has been the subject of extensive research and these studies demonstrate that digital scans accurately reproduce the dentition and intraoral structures as a digital model (Brown et al. 2018; Medina-Sotomayor et al. 2018). With confidence established in the scanning process, attention should be turned to evaluating the actual 3D printing process and outcomes.

It is important to note that the parameters for clinical accuracy are driven by the application of the 3D printing technology, for example, there are different acceptable standards of accuracy for 3D printing technology used for restorative dentistry versus clinical orthodontics. Studies investigating the use of 3D-printed full-coverage crowns have set clinical acceptability at 0.1 mm marginal gap, meaning that any deviation of more than 0.1

mm from the master model or prepared tooth was classified as outside the range of acceptability (Osman et al. 2017; Rungrojwittayakul et al. 2020). 3D-printed orthodontic models are evaluated based on how well it duplicates the dimensions of the patient or original master model. Some studies suggest that any deviation less than ±0.5 mm is considered clinically acceptable (Camardella et al. 2017; Sherman et al. 2020). However, when 3D-printed models are used for clear aligner fabrication a higher degree of accuracy is required with an absolute intra-tooth deviation of more than ±0.25 mm being unacceptable for fabrication of an active appliance (Short et al. 2018; Williams et al. 2022). Measurements that consider more than one tooth, i.e., inter-tooth measurements such as measurements across the arch, have a larger range for error of ±0.5 mm since they include two separate teeth. Each clear aligner has a maximum tooth movement range of 0.25 to 0.3 mm, therefore deviations outside this range would negatively impact clinical efficacy of the aligner (Kim et al. 2018).

Utilizing the determined parameters for clinical accuracy, researchers are evaluating 3D-printed models with a variety of manual and digital methods. Currently, there are no ISO (International Organization for Standardization) specifications for 3D-printed dental models for use in orthodontics. This allows for latitude with regards to methods of evaluation that have been used to date.

For example, Brown et al. reported that in an experiment comparing traditional stone models and their 3D-printed counterparts, digital calipers were used to directly measure crown width, crown height, inter-canine width, intermolar width, and arch length to the nearest 0.01 mm on both the stone and 3D-printed models. After obtaining a total of 6480 measurements, they concluded that there was no statistically significant difference between the traditional stone and 3D-printed models on all measurements except for crown height. The average crown height measurement was significantly shorter by 0.29 mm for the DLP 3D-printed models when compared to the stone models. This suggests that the DLP 3D-printed models may underestimate true crown height. They determined that despite this statistically significant difference, when compared to a previously established range of error of 0.20 to 0.50 mm for orthodontic clinical acceptability, the 0.29 mm average difference was not clinically significant, and the use of 3D-printed models should be considered clinically acceptable (Brown et al. 2018).

Another evaluation technique described by Loflin et al. employed the American Board of Orthodontics (ABO) Cast-Radiograph Evaluation (CRE) grading system to assess traditional stone models and their 3D-printed counterparts. The ABO CRE was developed as an objective assessment for treatment outcomes of cases presented at the ABO clinical exam. While the ABO clinical exam has moved from a case presentation to a scenario-based format, the CRE is still a viable method for evaluation of posttreatment orthodontic cases. The CRE grading system assigns scores based on tooth alignment/rotations, uniform marginal ridge heights, buccolingual inclination, overjet, occlusal contacts, inter-arch occlusal relationships, interproximal contacts, and root angulation. The primary independent variable of this study was print layer thickness and its effect on the ABO CRE total score. Models 3D printed at 25 µm, 50 µm, and 100 µm were graded against their traditional stone model counterparts using the ABO CRE rubric. A comparison of each model type's scores revealed that the stone models and all 3D-printed model types were highly positively correlated for the total score with 100 µm models being the most highly correlated. They conclude due to the lack of statistically significant differences and increased speed of printing, 3D-printed models printed at a layer thickness of 100 µm should be considered clinically acceptable (Loflin et al. 2019).

While instrumental in furthering the discussion of 3D-printed dental model evaluation, it can be argued that the above techniques of direct measurements may not represent the most accurate methods of evaluation. For this reason, much of the recent literature has employed the use of digital analysis using metrology software in the evaluation of clinical accuracy of 3D-printed models (Short et al. 2018; Choi et al. 2019; Dong et al. 2020; Kennings 2020; Ko et al. 2021; Williams et al. 2022; Dias Resende et al. 2023). With digital analysis, traditional linear measurements can be made but much of the value lies in the ability to superimpose STL files of digitally scanned master models and experimental 3D-printed models. The STL files are accurately aligned by computerized algorithms that calculate the ‘best fit’ using structure and voxel recognition after which all deviations between the two scans are calculated. After setting parameters, data can then be presented quantitatively with numerical values and qualitatively with a superimposition heat map. Traditionally in these heat maps, cooler colors indicate the experiment model is smaller than the master, warmer colors indicate the experimental is larger than the master, and green indicates the two digital scans are coincident.

In a recent study, Ko et al. used a digital analysis technique to compare models that were printed at various combinations of layer thicknesses (20 µm, 50 µm, and 100 µm) and build angles (0°, 30°, 60°, and 90°). After the models were 3D printed, they were each scanned to create an experimental model STL. This experimental model STL was compared to the master model STL using digital superimposition (figure 2) (Ko et al. 2021). Citing previous studies, parameters for clinical accuracy were set at ±0.25 mm, meaning that any point on the experimental model STL that deviated either positively or negatively by more than 0.25 mm from the master model STL was considered out of bounds (Favero et al. 2017). Using this digital analysis, researchers were able to quickly note several interesting deviation patterns with regards to the entire 3D model and not just predetermined 2D measurements. They concluded that build angle and print layer thickness have an interactive relationship that affects the dimensional accuracy of a 3D-printed model. They also determined that DLP 3D-printed models at a print layer thickness of 20 µm and a build angle of 0° are not clinically accurate for clear aligner therapy, while all other print thickness and build angle combinations were clinically acceptable.

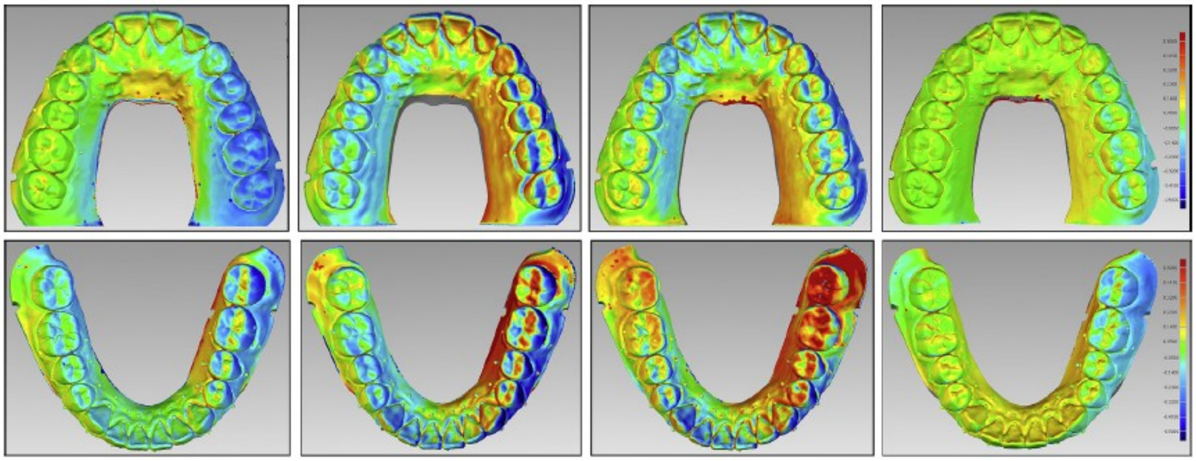

Figure 2. Digital superimposition heat map. Adapted from Kim et al. 2021.

Factors that Influence Clinical Accuracy of 3D-printed Models

Type of Printer

There are many different types of 3D printers available to the consumer, each with their own relative strengths and weaknesses. The most common types of printers used in a clinical dental setting are the stereolithography apparatus (SLA) and the digital light processing (DLP). Both SLA and DLP printers have become more popular in a private practice setting due to their small form factor, ability to print clinically accurate models relatively quickly, and relative low cost (Arnold et al. 2019; Zhang et al. 2019). Both printers are referred to as vat polymerization printers, meaning that they utilize a vat of photosensitive resin, a light source, and a mobile printing platform. The floor of the vat of resin is transparent and it sits above the light source. When printing begins, a platform descends into the vat displacing the liquid resin and stops a set distance away from the transparent floor, typically between 20-100 µm. Next, a light source shines through the transparent floor and cures the thin layer of resin between the floor and the platform. Then the platform rises slightly to allow another layer of liquid resin to flow between the floor and previously cured layer. Another layer is cured, and this pattern continues until the entire structure is made (Dawood et al. 2015).

The primary difference between SLA and DLP printers is the light source. SLA printers use a series of mirrors to direct a single laser to move along the contours of the layer to be printed and cure the resin. Instead of a single laser, DLP printers use a high-resolution light projector to project the shape of the entire layer to be printed and cure that layer all at once (Choi et al. 2019). These two processes, while similar, are different enough to have justified research to determine which type of printer is more appropriate for clinical orthodontic applications.

Several studies have been performed to determine the accuracy of SLA and DLP printers. While many studies have shown that there is a significant difference in their accuracies, the statistically significant differences rarely translate to clinical significance when compared to the 0.25 mm acceptable deviation discussed above. In these studies, the models were printed with a solid body in a horseshoe shape (hard palate and floor of mouth missing - clinically valuable when making thermoformed clear aligners) and with the occlusal plane facing up (Brown et al. 2018; Kim et al. 2018; Sherman et al. 2020). Under these conditions, there is sufficient evidence to suggest that both SLA and DLP printers can be accurately used in orthodontic clinical applications. When compared to SLA printers, DLP printers are generally accepted to be more efficient at printing which makes them a more common selection for private practices (Sherman et al. 2020).

Model Body Type: Shell vs Solid

With respect to thermoformed clear aligner fabrication, a horseshoe-shaped model that only includes the actual dental arch is important because it allows for easy removal of the thermoformed aligner without distortion. Another modification to the models that has been studied is a solid model body vs a shell model body. A shell model body type in theory reduces cost of fabrication by decreasing the amount of resin required. Naturally, reduced fabrication cost has made this option interesting to many practitioners and has justified research to determine if changing the model body type from solid to shell has negative effects on clinical accuracy. Several studies have demonstrated that when the shell models were designed with a wall thickness of at least 2 mm there was no significant difference compared to the solid models (Kennings 2020; Rungrojwittayakul et al. 2020). Arnold et al. also found no significant difference in accuracy between the solid and shell model body types and highlighted several important considerations for those using this technique. Shell models require additional pre-printing digital processing to create a "vent hole" that allows the uncured liquid resin to escape the model and prevent liquid resin capture (Arnold et al. 2019). This additional time may make the shell model body type less appealing to many providers. These considerations in combination with the methods performed in many contemporary studies have led to the solid model being more commonly used (Brown et al. 2018; Kim et al. 2018; Dong et al. 2020; Ko et al. 2021).

Print Layer Thickness

As pixels relate to image resolution of a two-dimensional image, z-axis resolution or print layer thickness relates to resolution of a 3D-printed object (figure 3). Typical print layer thicknesses from desktop 3D printers range from 20 µm to 100 µm. A smaller print layer thickness results in a final print with a smoother surface finish and finer details but will take longer to complete than the same print job done at a larger print layer thickness since there are an increased number of layers to be completed (Martorelli et al. 2013).

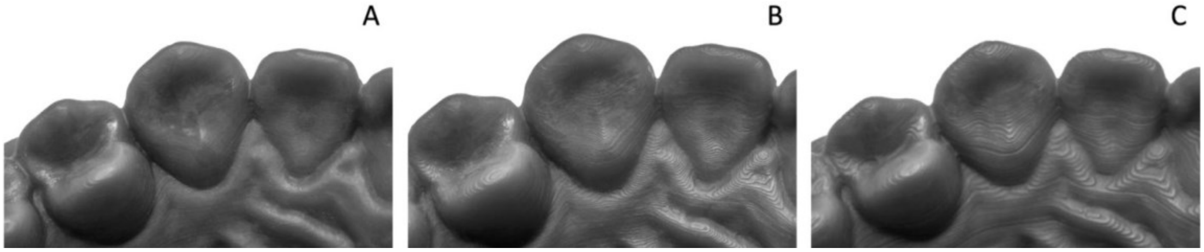

Figure 3. Dental models printed at various print layer thicknesses. Models are printed at (A) 25 µm (B) 50 µm, and (C) 100 µm. Loflin et al. 2021.

While a decreased print layer thickness would intuitively seem to result in a more accurate final print, recent literature calls this concept into question. Currently, there is much debate as to the benefits and drawbacks associated with print layer thickness in an orthodontic application. Some of the current research reports that the smaller the print layer thickness, the more accurate the final product (Martorelli et al. 2013; Alharbi et al. 2016). Other articles postulate that with smaller print layer thickness and an increased print layer number comes a higher chance for error and deterioration of the final print accuracy (Zhang et al. 2019). Still further research indicates that there is no significant association between accuracy of orthodontic models and print layer thickness (Loflin et al. 2019; Dias Resende et al. 2023).

As demonstrated above, accuracy requirements of the final print are driven by the clinical procedure with restorative dentistry requiring much higher accuracy than orthodontic clear aligner fabrication. This larger range of clinical acceptability justifies orthodontic users to print at larger layer thicknesses for more rapid fabrication and delivery of the aligners to the patient. As one of the primary settings that a clinical user can manipulate to decrease production time, the effect of alterations in print layer thickness needs to be quantified. Furthermore, a brand DLP printer[1] commonly used in private practice clear aligner fabrication, recently released an update in June of 2020 that allows users to print at 170 μm. Research is required to evaluate the accuracy of 3D-printed models fabricated at this new layer thickness.

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[1] SprintRay Pro, SprintRay, 20321 Valencia Cir, Lake Forest, CA 92630

Build Angle

Build angle is another variable that is easily manipulated by the operator to increase production efficiency (figure 4). For example, models printed with their base parallel to the print platform take up more room than models printed with their base perpendicular to the print platform. This means that more models may be printed simultaneously when the operator utilizes a build angle other than horizontal. Clear aligner fabrication requires the use of a high number of models, so it may be advantageous to print as many models as possible in each batch. It is important to note that at angles between 0° and 70°, support structures are placed between the model and the print platform to support the model as it prints. These support structures require increased post-processing time to remove and are therefore commonly avoided by printing at build angles that do not require supports.

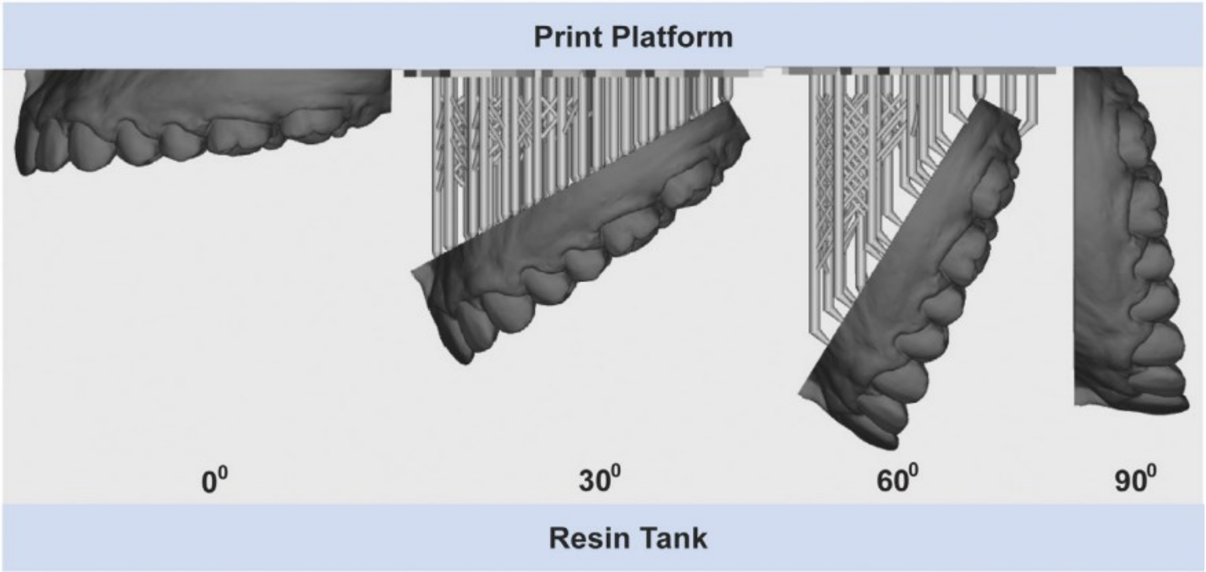

Figure 4. Dental models printed at various build angles. Adapted from Ko et al. 2021.

Despite improved efficiency with varying build angles, the angle at which an object is 3D printed has been shown to impact the accuracy of the final print. For example, several studies have printed full-coverage crowns at various angles and found that the build angle directly affected the dimensional accuracy with some build angles producing crowns that adapted more accurately than other build angles (Alharbi et al. 2016; Ryu et al. 2020). Shim et al. came to a similar conclusion in a study evaluating the accuracy of a printed bar (2020).

Few studies have addressed the relationship between build angle and accuracy of orthodontic models. Short et al. utilized an SLA printer to print models with a solid horseshoe shape and tested three build angles: flat (0°), 20° and perpendicular (90°). The researchers found that all three build angles produced models that within the range of clinical acceptability (±0.25 mm) (Short et al. 2018). This study was significant in opening the discussion on build angles for orthodontic models. Further research is needed to extend the information available. For example, will different build angles using a DLP printer behave the same way? Is there an optimal print angle that allows increased printing efficiency and retains clinical accuracy? The effect that build angle has on the accuracy of the 3D-printed orthodontic models, specifically using DLP technology, is an area that needs additional exploration.

Interactions Between Print Layer Thickness and Build Angle

Print layer thickness and build angle are the most common settings for an operator to manipulate during clear aligner fabrication. Each setting individually has been shown to influence the accuracy of the final model, but few studies have examined the relationship between these two variables and the outcome of different combinations of various print layer thicknesses and build angles. Printing dental models utilizing an SLA printer, Arnold et al. demonstrated that the print layer thickness in concert with the build angle have a large effect on the surface smoothness of the final print (2019). Ko et al. further contributed to this area of research by combining different print layer thicknesses (20 µm, 50 µm, and 100 µm) with various build angles (0°, 30°, 60°, and 90°). Their conclusion was that there is a dependent relationship between build angle and print layer thickness impacting the accuracy of the final print (Ko et al. 2021). However, this study did not include a print layer thickness of 170 µm since this setting was not available at time of publication. Further research is needed to determine if there is an optimal angle to print dental models at 170 µm for greater clinical accuracy.

Problem Statement

The constant advancements and expanding technical abilities in the field of 3D printing brings uncertainty to dental practitioners about whether this new technology is an accurate and efficient replacement for more traditional methods. With each new iteration of 3D printing settings, further research is required to quantitatively confirm "best practice" 3D printing procedures. While 100 µm is the currently the most commonly used print layer thickness, a recent update has allowed users to print at a layer thickness of 170 µm. Although potentially more efficient, this print layer thickness has not yet been assessed in the literature and research is needed to evaluate its accuracy for use in the fabrication of clear aligner therapy. The purpose of this research is to evaluate the accuracy of dental models printed using a popular desktop DLP 3D printer at the most common print layer thickness and the newly available thickness and at various clinically useful build angles to determine if this new setting is appropriate for use in clear aligner fabrication.

Hypothesis

1. The accuracy of 3D-printed orthodontic models will vary as a function of the build angle and print layer thickness when compared with selected value of clinical accuracy (±0.25 mm).

CHAPTER 2

MATERIALS AND METHODS

Developing the Master Model

The master model was developed using the maxillary arch of an ideal typodont[1]. The typodont has a glossy finish that is too reflective and would not allow an accurate digital scan, therefore a stone model of the typodont was created and used as the master model. The 3rd molars were removed from the typodont dentition to better represent the more common clinical scenario and a vinyl polysiloxane[2] (VPS) impression was obtained. Once the VPS impression was fully set, vacuum mixed[3] type III stone[4] was be poured into the impression. Next, the fully set stone model was removed, trimmed, and scanned with a desktop 3D scanner[5] to generate an STL file. This STL file served as the “Master Model” and all future comparisons for evaluation of accuracy were done against this STL file.

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[1] Kilgore, NISSIN 200 Type, Kilgore International, Inc., 595 W Chicago St, Coldwater, MI 49036
[2] Aquasil Ultra Monophase, Dentsply Sirona, 13320 Ballantyne Corporate Place, Charlotte, NC 28277
[3] Whipmix Vacuum Power Mixer Plus, 361 Farmington Ave, Louisville, KY 40217
[4] Pemstone Golden, Garreco LLC, 430 Hiram Rd., Heber Springs, AR 72543
[5] Medit T710, MEDIT corp. 23 Goryeodae-ro 22 gil, Seongbuk-gu, Seoul, Korea

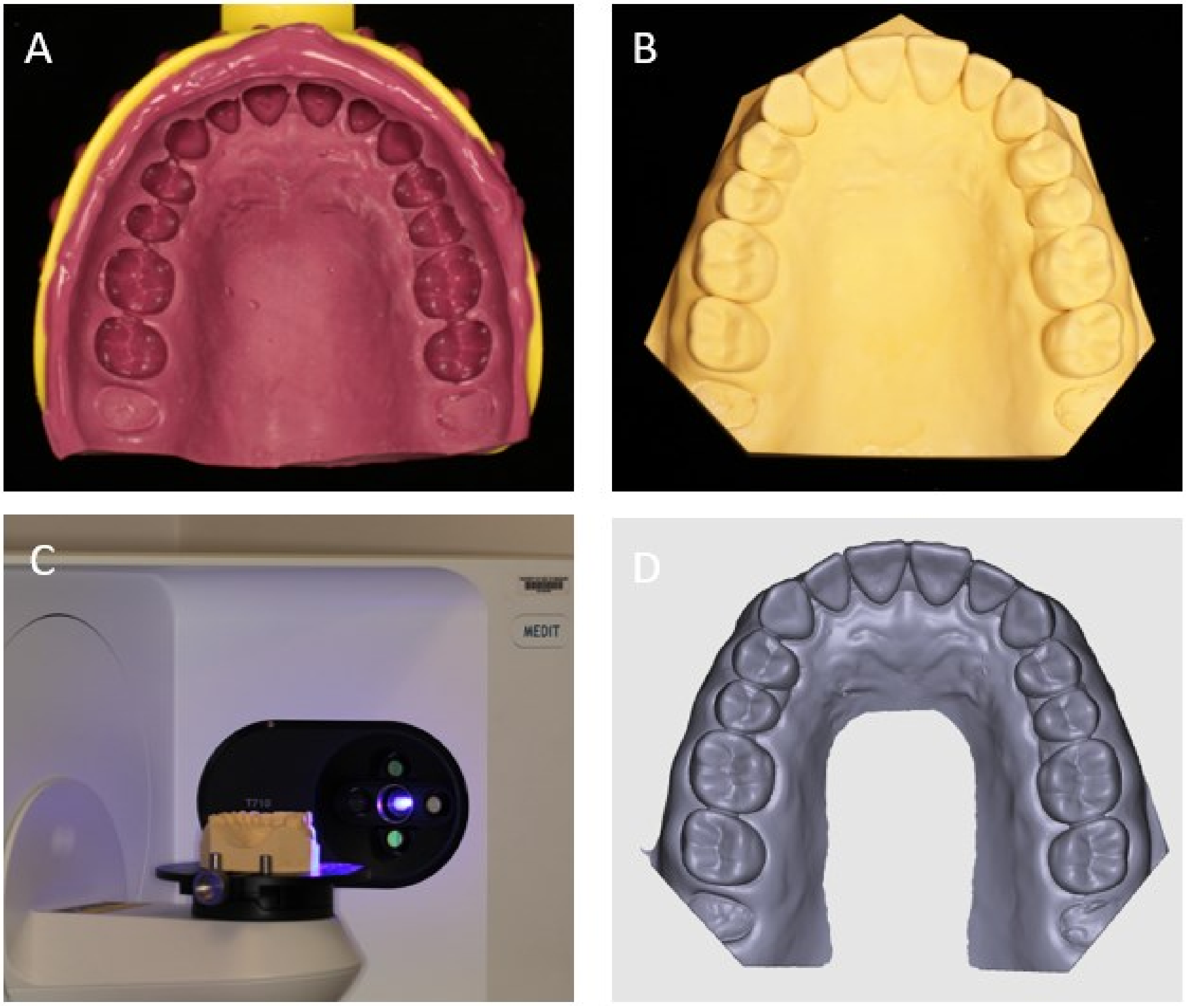

Figure 5. Stages of digital master model development. A. Occlusal view of VPS impression use to fabricate stone model. B. Occlusal view of stone model. C. Stone model being scanned by desktop scanner[5] D. Occlusal view of Master Model STL file.

3D Printing of the Experimental Models

After fabrication and subsequent scanning of the master model, experimental models were 3D-printed from the Master Model STL. The experimental models were printed in a horseshoe configuration with a solid base that extended 3 mm beyond the gingival margin of the central incisors and 6 mm beyond the gingival margin at the first molars. The experimental models were printed at three build angles: 0° (parallel to the print platform), 70°, and 90° (perpendicular to the print platform) (figure 6). These build angles were selected because they did not require supports while printing, required less post-print processing time, and therefore were more efficient than build angles that did require supports. The angles of 70° and 90° also have the advantage of a smaller footprint on the print platform compared to 0°, therefore more models may be printed at the same time. The experimental models were printed at two print layer thicknesses: 100 µm and 170 µm (figure 7). The 100 µm layer thickness was selected due to its representation in the literature of an accurate print layer thickness and these models acted as a validation of the current protocol via comparison to previous studies, while the 170 µm layer thickness was selected to test the accuracy of 3D-printed models at this newly released and more efficient print layer thickness (Loflin et al. 2019; Ko et al. 2021). The models were printed on a calibrated benchtop DLP printer[6] using a photosensitive polymer liquid resin[7].

Each experimental model combination (100 µm-0°, 100 µm-70°, 100 µm-90° and 170 µm-0°, 170 µm-70°, 170 µm-90°) were printed ten times for a total of sixty experimental models. Printing of the sixty experimental models was divided into two sets of five groups (figure 8). One set of five groups was completed at the print layer thickness of 100 µm, the other set was completed at the print layer thickness of 170 µm. Each of the five groups contained two models of each build angle (0°, 70°, 90°) for a total of six experimental models per group. Previous research suggests that model location on the print platform is a potential confounding variable when analyzing final accuracy (Sherman et al. 2020). To minimize this variable, the 3D printing software[8] was used to create a different arrangement

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[6] Sprintray Pro, SprintRay, 20321 Valencia Cir, Lake Forest, CA 92630
[7] Die and Model Tan 2, SprintRay, 20321 Valencia Cir, Lake Forest, CA 92630
[8] RayWare v 2.8.9, SprintRay, 20321 Valencia Cir, Lake Forest, CA 92630

of models in each of the five groups. Each model was identified by print layer thickness, build angle, and print group.

After printing completion, each experimental model was processed according to the manufacturer recommendations. First, the models were removed from the print platform and washed in an ultrasonic cleaner[9] containing 99% isopropyl alcohol (IPA) for five minutes and then thoroughly dried. Afterwards, the models were placed into a desktop curing unit[10] at the recommended time and temperature (30 min at 30 °C) achieve a complete cure of the resin.

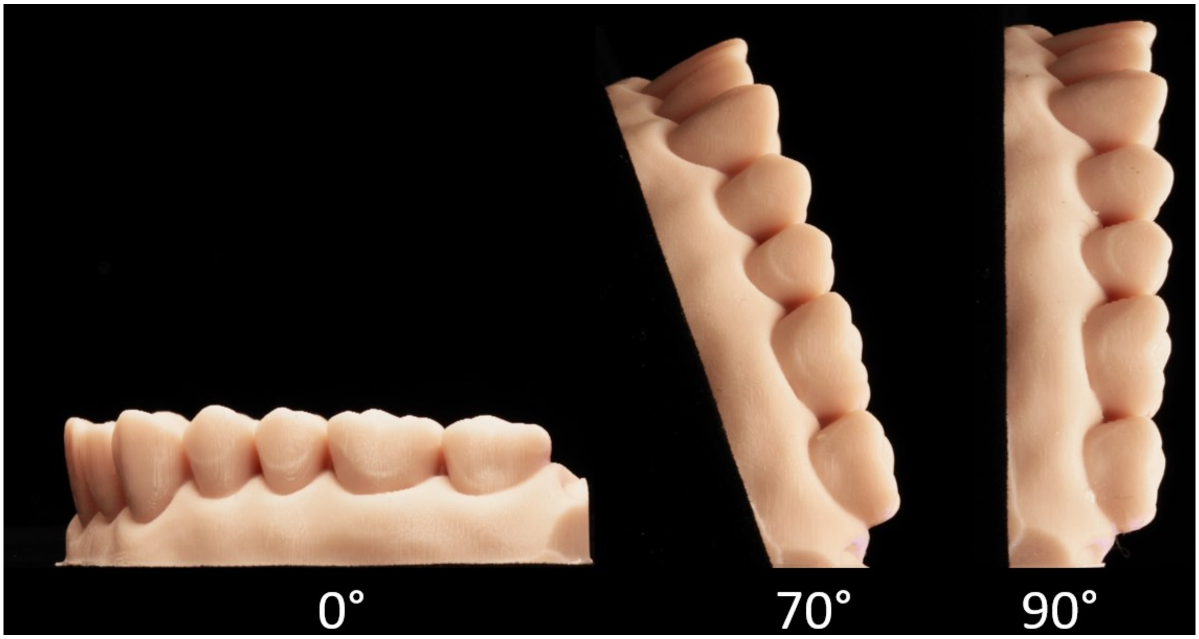

Figure 6. Experimental model build angles (0°, 70°, 90°).

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[9] Form Wash, Formlabs Inc., 35 Medford St. Suite 201, Somerville, MA 02143
[10] Form Cure, Formlabs Inc., 35 Medford St. Suite 201, Somerville, MA 02143

Figure 7. Experimental model print layer thicknesses. Experimental models printed with a layer thickness of 170 µm (above) and 100 µm (below) at a build angle of 0°.

Figure 8. Experimental model print batches. Each of the five print batch arrangements with three build angles and two models per build angle.

Creation of Experimental Model STL Files

Once the experimental models were 3D-printed and post-processed according to manufacturer's recommendations, creation of the experimental model STL files was completed using the same desktop 3D scanner[11] used to create the master digital model. Each experimental model STL file was then be saved with a filename that identifies the print layer thickness, print group, and build angle (e.g. [100-1] 0A, [170-4] 70B).

Evaluation of Experimental Model Accuracy

In accordance with much of the recent literature on 3D-printed dental model evaluation, the experimental model STL files were compared to the digital master model STL file using a metrology software[12] (Short et al. 2018; Choi et al. 2019; Dong et al. 2020; Kennings 2020; Ko et al. 2021; Williams et al. 2022; Dias Resende et al. 2023). This software superimposed two separate STL files to compare their respective point clouds and calculate discrepancies between the two. The master model STL file was loaded into the software and assigned to the "reference" data. Excess material was digitally trimmed off the master model STL file to minimize error with the alignment process. To focus our analysis on the area of the model that would be used to fabricate clear aligners, the "Resegmentation" tool was used to create a "region" that encompasses the dentition and the typical trimline of the aligners which is a straight line connecting points about 0.5 mm gingival to the zenith of the gingival margins of the teeth. This is the area that is used to clinically fabricate clear aligners and as such is the area of highest interest with regards to accuracy. This region was

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[11] Medit T710, MEDIT corp. 23 Goryeodae-ro 22 gil, Seongbuk-gu, Seoul, Korea

[12] Geomagic Control X v 2023.0, 3D Systems, Rock Hill, SC 29730

then selected for digital superimposition and subsequent 3D analysis to avoid incorporating any outlying measurements from areas that are not used to clinically fabricate clear aligners.

Experimental model STL files were then be loaded and assigned as the “measured” data. The reference and measured objects were brought into initial alignment prior to using the software’s “Best Fit Alignment” tool. The software used an iterative closest point algorithm to compute and minimize the sum of squares of distances between the point clouds to further align the models. The alignment was performed using the re-segmented area that is used to clinically fabricate aligners. Once alignment was completed, the software’s “3D Comparison” tool was used for 3D analysis to quantify any cloud point deviations between the digital master model and experimental model STL files. As noted previously, the bounds of clinical accuracy were set at ±0.25 mm and this range was identified as “tolerance” in “3D Comparison” tool. This range was selected based on previous studies that examined the accuracy of 3D-printed models as well as the average thickness of the periodontal ligament space (Favero et al. 2017; Ko et al. 2021). The software calculated all deviations between the cloud points of the master model STL file and cloud points of the experimental model STL file (reference and measured data respectively) to develop a color map display. All areas of the experimental model with cloud points that lie within the set tolerance (±0.25 mm) were displayed as green. Any areas of deviation outside of this set range of ±0.25 mm were displayed as either a warm color or a cool color for positive or negative deviations respectively, with gradations of intensity to display the magnitude of the deviation. Individual cloud points could be selected for deviation quantification (figure 9).

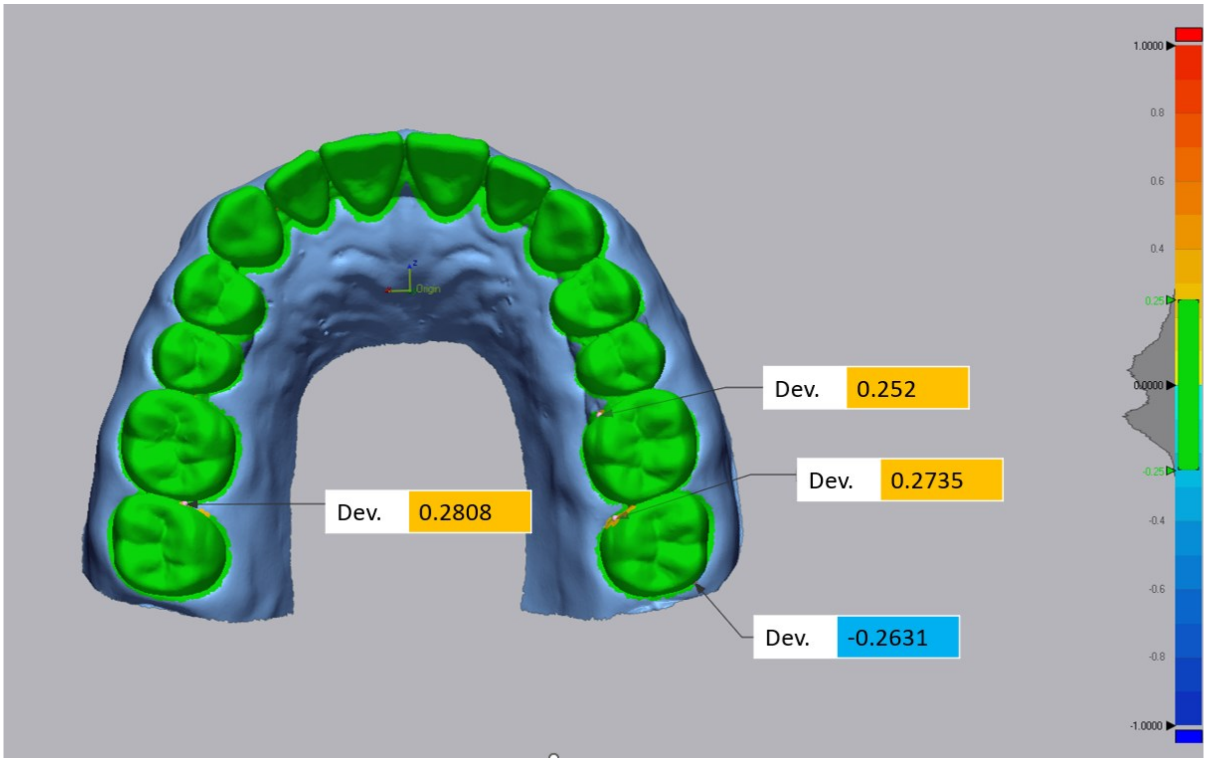

Figure 9. Experimental digital superimposition representation. Color map with accuracy threshold set at ±0.25 mm. Locations marked are cloud points outside of this range of clinical acceptability.

Experimental Design

This experiment was a laboratory study that used a two-factor design. The first independent variable was the print layer thickness: 100 µm or 170 µm. This changes the speed at which prints can be completed and therefore directly affects the print time. The second independent variable was the angle at which the model is printed relative to the printing platform. This changes the orientation of the printed layers which affects the surface smoothness as well as the footprint of the models on the print platform, altering the number of models that can be printed at one time. The build angles were 0° (horizontal), 70°, and 90° (vertical).

The dependent variable in this experiment was the clinical accuracy of the experimental models. This was determined by digital superimposition with an accuracy threshold set at ±0.25 mm. Measurements were taken to determine the percentage of experimental model cloud points that are within the range of clinical accuracy. Experimental model cloud points outside the range of clinical accuracy were broken down into the following two variables: the percentage of the model's cloud points that are positively deviated (larger than +0.25 mm), and the percentage of the model's cloud points that are a negatively deviated (smaller than -0.25 mm). The mean of each of these measurements for all ten models of a given type (i.e. 100 µm - 0°) was presented to give a representation of the clinical accuracy of that type of model (table 1).

Categorical data was also collected to identify the locations of deviations outside of the range of clinical accuracy (±0.25 mm). Positive and negative deviations were recorded as a simple count and organized by location as follows: buccal of the incisors, lingual of the incisors, buccal of the canines, lingual of the canines buccal of the premolars, lingual of the premolars, buccal of the molars, lingual of the molars (table 1).

The sample included a total of sixty test models made up of six groups of ten model types: (100 µm–0°, -70°, -90° and 170 µm–0°, -70°, -90°).

TABLE 1

EXPERIMENTAL DESIGN

Independent Variables		Dependent Variables											
Model Groups (10/group)		Clinically Accurate Models (%)	Cloud Points within Tolerance* (Mean%)	Positively Deviated Cloud Points (Mean %)	Negatively Deviated Cloud Points (Mean %)	Deviation Location**							
Print Layer	Print Angle					Positive				Negative			
						I	C	P	M	I	C	P	M
100 µm	0°					B				B			
						L				L			
	70°					B				B			
						L				L			
	90°					B				B			
						L				L			
170 µm	0°					B				B			
						L				L			
	70°					B				B			
						L				L			
	90°					B				B			
						L				L			

*Tolerance: Range of clinical accuracy (±0.25 mm).

**Deviation Location: Observational data referring to locations of deviation, either positive or negative as noted. Abbreviations: Incisors (I), Canine (C), Premolar (P), Molars (M), Buccal (B), Lingual (L).

Data Analysis

Data analysis included an evaluation of the clinical accuracy of the experimental models as they compared to the digital master model. The mean percentage of cloud points that lie inside of the range of clinical acceptability (±0.25 mm) was calculated for each model type. Positive and negative deviations, deviations that are greater than +0.25 mm or smaller than -0.25 mm respectively, were analyzed and the mean percentages of these values were calculated. Observational data pertaining to the deviation location was analyzed to determine if there was a pattern of deviation location among print layer thickness and build angle combinations.

CHAPTER 3

RESULTS

Table 2 presents the mean percentage of cloud points that were within the range of clinical acceptability (±0.25 mm) for all six model types. Also presented are the mean percentages of both positively and negatively deviated cloud points for all six model types. In this experiment, there was no model type that exhibited 100% of cloud points inside the range of clinical acceptability. For all model types, the range of mean percentage of cloud points that lie within the range of clinical acceptability has a minimum value of 92% (100 µm-90°) and a maximum value of 97% (170 µm-70°).

Models with a print layer thickness of 100 µm exhibited the following mean percentage of cloud points within the range of clinical acceptability: 95% (100 µm-0°), 94% (100 µm-70°), and 92% (100 µm-90°). The range of clinically unacceptable cloud points were as follows: -0.53 to +0.65mm (100 µm-0°), -0.46 to +0.45mm (100 µm-70°), and -0.71 to +0.66 mm (100 µm-90°). Most cloud points outside of the range of clinical acceptability tended to deviate in a negative direction (table 2). The majority of these deviations were located on the buccal surface of the premolars and molars when printed at 0°, 70°, and 90°. The buccal surface of the canines also exhibited negative deviations when models were printed at 70° and 90° (table 3).

Models with a print layer thickness of 170 µm exhibited the following mean percentage of cloud points within the range of clinical acceptability: 96% (170 µm-0°), 97% (170 µm-70°), and 96% (170 µm-90°). The range of clinically unacceptable cloud points were as follows: -0.37 to +0.64mm (170 µm-0°), -0.39 to +0.48mm (170 µm-70°), and -0.70 to +0.70 mm (170 µm-90°). Most cloud points outside the range of clinical acceptability tended to deviate in a positive direction (table 2). There were more positive deviations on the lingual surface of all model teeth when the models were printed at 0°. There were more negative deviations when the models were printed at 70° and 90° and these deviations tended to be located on the buccal surface of all teeth and the lingual surface of the molars (table 3).

The results of this study support our hypothesis that the accuracy of 3D printed dental models will vary as a function of build angle and print layer thickness.

TABLE 2

EXPERIMENTAL MODEL MEASUREMENTS

Model Groups (10/group)		Clinically Accurate Models (%)	Cloud Points within Tolerance* (Mean%)	Positively Deviated Cloud Points (Mean %)	Negatively Deviated Cloud Points (Mean %)
Print Layer	Print Angle				
100 µm	0°	0	95	2	3
	70°	0	94	2	4
	90°	0	92	2	6
170 µm	0°	0	96	4	0
	70°	0	97	2	1
	90°	0	96	2	2

*Tolerance: Range of clinical accuracy (±0.25 mm).

TABLE 3

EXPERIMENTAL MODELS DEVIATION LOCATIONS

Model Groups (10/group)		Number and Location of Deviations *									
Print Layer	Print Angle		Positive					Negative			
			I	C	P	M		I	C	P	M
100 µm	0°	B	0	0	0	1	B	0	0	6	8
		L	0	0	2	2	L	0	0	0	2
	70°	B	0	0	2	2	B	0	6	6	8
		L	0	0	0	0	L	0	0	2	2
	90°	B	0	0	0	2	B	1	8	8	8
		L	1	0	0	0	L	0	0	2	9
170 µm	0°	B	0	0	1	0	B	0	0	0	0
		L	1	2	5	6	L	0	0	0	0
	70°	B	0	0	0	0	B	1	3	2	10
		L	1	2	1	0	L	0	0	0	10
	90°	B	0	0	0	1	B	4	5	5	10
		L	1	1	2	0	L	0	0	0	9

*Deviation Location: Observational data referring to locations of deviation, either positive or negative as noted. Abbreviations: Incisors (I), Canine (C), Premolar (P), Molars (M), Buccal (B), Lingual (L).

CHAPTER 4

DISCUSSION

The rapidly advancing field of 3D printing has led to significant changes in the workflow of the average orthodontic practice. Consequently, there has been a surge of interest in determining the accuracy of these new digital methods. Previous studies have investigated the effect of different positions of the object on the print platform (Sherman et al. 2020), print layer thickness (Loflin et al. 2019), and build angle (Short et al. 2018; Ko et al. 2021). Another study tried to determine the difference in model accuracy produced by various types and brands of 3D printers (Kim et al. 2018). Many of these studies used digital superimposition software to determine accuracy of the 3D-printed models (Short et al. 2018; Choi et al. 2019; Dong et al. 2020; Kennings 2020; Ko et al. 2021; Williams et al. 2022; Dias Resende et al. 2023). These studies have largely concluded that 3D printed models produced by commercially available 3D printers are accurate for clinical application; however, each study also demonstrated an effect on clinical accuracy with changes in type of printer, the print layer thickness, and build angle. The aim of the present study was to evaluate the accuracy of 3D printed models fabricated on a DLP printer with different combinations of print layer thicknesses (100 µm and 170 µm) and build angles (0°, 70°, and 90°) using digital superimposition analysis.

The effect of varying print layer thicknesses on the accuracy of 3D printed models has been investigated in several studies. In a study by Zhang et al., models were printed at a build angle of 0° using three different DLP printers with layer thickness of 20 µm, 30 µm, 50 µm, and 100 µm. They found that models printed at 50 µm were more accurate than the models printed at 20 µm, 30 µm, and 100 µm. They postulated that models printed using a thinner print layer thickness were composed of a greater number of cured layers than models printed at a thicker print layer thickness (Zhang et al. 2019). This increased number of cured layers could compromise the overall dimensional accuracy of the printed model. Other studies conclude that there is no significant association between print layer thickness and clinical accuracy of 3D printed models (Loflin et al. 2019; Dias Resende et al. 2023). To date, no other study has compared models printed on a DLP printer using print layer thicknesses of 100 µm and 170 µm. The results of the present study indicate that models printed at 170 µm may be slightly more accurate than models printed at 100 µm, which may coincide with the explanation set forth by Zhang et al.

Numerous studies have explored the impact of adjusting the build angle on the precision of 3D printed models. In a study conducted by Short et al., orthodontic models were fabricated using an SLA printer, employing build angles of 0°, 20°, and 90°. Their findings indicated that all three build angles yielded clinically accurate models (Short et al., 2018). Conversely, distinct investigations by Shim et al. and Ryu et al. assessed the effects of varying build angles on the accuracy of printed provisional crowns and resin denture bases, respectively. Upon evaluating the intaglio surface of each, both Shim et al. and Ryu et al. concluded that build angle significantly influences the accuracy of the final print. (2020; 2020). Given the differing clinical requirements for prosthodontic and orthodontic applications of 3D-printed models, these conclusions may not be directly applicable to orthodontic practice.

The findings of our current study reveal that, when controlling for print layer thickness, variations in build angle did impact model accuracy. Specifically, models printed at 100 µm and 0° exhibited a mean percentage of clinically accurate cloud points of 95%, whereas those printed at 100 µm and 90° showed a mean percentage of 92%. However, models printed at a print layer thickness of 170 µm exhibited a less pronounced difference between build angles. Models printed at 170 µm and 0° as well as 90° both displayed a mean percentage of clinically accurate cloud points of 96%. In both print layer thicknesses, models printed at 90° exhibited a greater number of negatively deviated cloud points in contrast to those printed at 0°. This indicates a discernible distinction in model accuracy across varying build angles when controlling for print layer thickness.

The interaction between build angle and print layer thickness on full dental models has also been previously evaluated (Ko et al. 2021). In this study, Ko et al. printed models using a DLP printer at various combinations of print layer thicknesses (20 µm, 50 µm, and 100 µm) and build angles (0°, 30°, 60°, and 90°). They concluded that there is a dependent relationship between build angle and print layer thickness that affects the accuracy of the printed models. The current study is the first to evaluate this dependent relationship using a larger print layer thickness and different build angles. The results confirm this dependent relationship that was described by Ko et al.

Clinical Implications

The goal of this study was to compare the clinical accuracy of 3D printed models with different combinations of print layer thicknesses (100 µm and 170 µm) and build angles 0°, 70°, and 90°). Models printed at 100 µm have already been shown to be clinically accurate, however, models printed at 170 µm have not been investigated (Lohfeld et al. 2024). Printing models at a larger print layer thickness allows print jobs to be completed faster since there are fewer total layers. On average, the printing process was about 30%

faster when printing at 170 µm compared to 100 µm. If a batch of models could be printed faster without sacrificing accuracy, it would allow a more efficient workflow.

The varying build angles are directly related to the number of models that can be printed at one time. A steeper build angle leads to a smaller footprint of an individual model on the print platform and allows greater total number of models to be printed in a single batch. The DLP printer used in the current study has a print platform that could print five models at 0°, twelve models at 70°, and fourteen models at 90°. Build angles between 0° and 70° often require support structures to be printed along with the model to prevent print failure. These supports must be removed before the model can be used, which costs operator time and effort. The present study investigated build angles that did not require 3D printed supports, which eliminates post-print time removing supports. A steeper build angle also increases total print time due to an increase in layers to be printed. If more models could be printed at once, it may increase efficiency. There are also clinical scenarios where a limited aligner series may require between five and fourteen models. It would be advantageous to use a steeper build angle to print the entire series at once without compromising model accuracy.

The results of this present study indicate that models printed at 170 µm at all three build angles were, on average, more accurate than the models printed at 100 µm. These results indicate that models can be printed at a faster rate without compromising clinical accuracy and increases the workflow efficiency of an orthodontic private practice.

Study Limitations

Limitations of the present study include the materials used, definition of clinical accuracy, and the use of an ideal typodont. First, only one DLP printer was used to print the models. There are many different brands and models of DLP printers being used in the orthodontic practice today, each with varying print settings and print platform dimensions. Thus, the results do not necessarily apply to all DLP printers, nor do they apply to any other type of 3D printer. While the current study did evaluate the novel and larger print layer thickness of 170 µm, this was the maximum print layer thickness for the DLP printer used and there was no opportunity to evaluate a print layer thickness larger than 170 µm. Additionally, the same resin was used to print all models. While some orthodontic offices may be using third party resins to reduce cost, it should be noted that variations in resin composition across brands may have an impact on print accuracy.

An important consideration of the current study was the evaluation of clinical accuracy. Clinical accuracy for 3D printed models has not been specifically defined by the International Standards Organization (ISO) as have impression materials and stone. The current literature offers considerations for clinical accuracy that range from 0.16 mm to 0.5 mm (Camardella et al. 2017; Short et al. 2018). The current study set the parameters of clinical accuracy to ±0.25 mm which reflects the width of the periodontal ligament and the amount of tooth movement expressed in each clear aligner. It should be noted that this range of clinical accuracy is specific to orthodontic purposes and cannot be applied to other applications.

Future Investigations

This study was designed to evaluate the accuracy of 3D-printed models with various print layer thicknesses and build angles. Future investigations could build on the aspects of the research done here and address some of the limitations of the current study. There is a need to confirm the findings of this study by investigating several different DLP printers and resin products from various brands to determine if a similar pattern of accuracy applies.

Print layer thickness is closely related to speed of print completion due to the alterations in number of layers to be cured. The current study only evaluated print layer thicknesses of 100 µm and 170 µm, but there are newer 3D printers that are capable of different thicknesses such as 150 µm. A study comparing all “high-speed” print layer thicknesses larger than 100 µm could be performed do determine an optimal speed and accuracy setting.

The average orthodontic patient has an initial malocclusion that often contains some level of crowding. A model with crowded teeth is morphologically different from a model with well aligned teeth as was used in this and other studies (Kim et al. 2018; Ko et al. 2021). This difference in tooth position and relationships with one another may cause alterations in print accuracy that has yet to be demonstrated in the literature. It may be that models with crowded teeth would be more accurately 3D-printed using different settings than models with no crowding. More importantly, the complex spatial relationships between misaligned teeth may result in either positive or negative deviations in the 3D-printed model that could lead to a deleterious effect on the biomechanical forces delivered by the thermoformed aligners.

CHAPTER 5

CONCLUSION

This study demonstrates that accurate orthodontic models can be 3D printed at varying build angles and print layer thickness. The greatest accuracy was demonstrated for models printed at a print layer thickness of 170 µm and a build angle of 70°.

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