

EFFECT OF BUILD ANGLE AND MODEL BODY TYPE (SOLID VS SHELL)  
ON ACCURACY OF 3D-PRINTED ORTHODONTIC MODELS  
USING A DLP PRINTER

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  
BRYNDON J BELNAP

B.S., Idaho State University, 2016  
D.D.S., Creighton University, 2020

Kansas City, Missouri  
2022



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Bryndon J. Belnap DDS, Candidate for the Master of Science Degree

University of Missouri-Kansas City, 2022

ABSTRACT

This study examined the effect that print angulation and model body type (solid vs. shell) have on the accuracy of orthodontic models printed with a digital light processing (DLP) 3D printer. The following six configuration of models were printed: 0° Solid, 0° Shell, 70° solid, 70° shell, 90° solid, and 90° shell. Eleven selected structures and distances were measured and compared against a digital master model.

Based on the comparisons made between the experimental models and digital master model, print angulation and model body type had little to no clinically relevant impact on the accuracy of the orthodontic models, with 98% of the raw measurements falling within the range of clinical acceptability, which was set at  $\pm 0.25$  mm for single tooth measurements (intra-tooth) and  $\pm 0.5$  mm for cross arch measurements (inter-tooth).

The overall results of this study suggest that altering print angulation and model body type according to the parameters set in this study, does not impact the clinical accuracy of 3D printed orthodontic models. These findings suggest greater flexibility of the practitioner to alter print settings to meet the needs of various clinical scenarios.

## 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 Model Body Type (Solid vs Shell) on Accuracy of 3D-Printed Orthodontic Models Using a DLP Printer,” presented by Bryndon Belnap, candidate for the Master of Science Degree in Oral and Craniofacial Sciences, and hereby certify that in their opinion it is worthy of acceptance.

### Supervisory Committee

Stefan Lohfeld, Ph.D., Committee Chair  
Department of Oral & Craniofacial Sciences

Mary P. Walker, D.D.S., Ph.D. Committee Co-chair  
Department of Oral & Craniofacial Sciences

Jean-Marc Retrouvey, DMD, M.Sc.  
Department of Orthodontics and Dentofacial Orthopedics

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## ACKNOWLEDGMENTS

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

Dr. Stefan Lohfeld for his expertise in 3D printing and thoughtful guidance.

Dr. Mary Walker for her guidance, structure and enthusiasm for my research and education.

Dr. Jean-Marc Retrouvey for his extensive clinical knowledge and guidance in developing my research question.

Marie Thompson for her help with formatting my thesis.

Jessica Moniz for her invaluable help in data collection, organization and analysis.

My wife, Tavia Belnap and my four daughters for their unwavering love and support.

My co-resident for their friendship, support, and encouragement throughout residency.

## CHAPTER 1

### INTRODUCTION

The advent of additive manufacturing is revolutionizing the way manufacturing is done. Three-dimensional printing or “3D printing”, as the process of additive manufacturing is commonly called, is finding applications in various fields and disciplines. Due to the high level of customization that 3D printing offers, it is being used in prototyping, biomechanics, and construction. Even materials for small houses have been 3D printed in less than a day in China. Since Charles Hull developed the technology in 1986, 3D printing has undergone changes and modifications to allow it to be used in increasingly specialized ways (Ngo et al. 2018). For example, the field of dentistry has undergone a substantial transformation as more dental processes are being digitized, from digital impressions, to milling devices, and now 3D printing. In orthodontics, among other applications, 3D printing of orthodontic models is an important step in the production of clear aligners that has typically been done in commercial dental laboratories. However, as the technology has continued to advance, it has been miniaturized and made available to private practices. As more private practitioners use this technology “in house,” variability in product quality and accuracy is likely to be of concern, especially as the printing process can be modified by the operator to save time and money. Consequently, many researchers have evaluated additive manufacturing and the factors that affect its accuracy. There is currently good evidence that suggests that the 3D printers used in orthodontics are adequately accurate for their intended applications when used according to manufacturer guidelines. However, the question remains whether or not the accuracy of 3D-printed orthodontic models is maintained when manufacturer guidelines are not followed, and more efficient modes of 3D printing are employed.

## **Advances in Technology in Dentistry**

In recent years, manufacturing in dentistry has undergone a significant transformation. Many manufacturing processes in dentistry require the use of dental models for the fabrication of crowns, dentures, splints, surgical guides, obturators for cleft palates, and orthodontic retainers, just to name a few. Traditionally, making the models has required impression materials (alginate, vinyl polysiloxane, polyether, etc.) that are used to capture a negative impression of the patient's teeth or other oral structures. After the impression material sets, a gypsum stone product or plaster is poured into the impression and allowed to harden. Once the stone sets, it is separated from the impression and can then be used for its intended purpose. This process has long been the standard protocol in dental offices and laboratories, but the relatively recent introduction of computer aided design/computer aided manufacture (CAD/CAM) technology has allowed for changes in this process to take place.

CAD/CAM technology has made it possible, in some cases, to completely replace the traditional workflow with a digital process. Instead of a tray of alginate impression material, a digital scanner is used to acquire the information in the form of multiple images that are stitched together to create an accurate 3D digital model. This technique has multiple advantages over the plaster equivalent. For example, digital diagnostic simulations can be accurately performed and then easily shared electronically with other providers or laboratory technicians. Additionally, digital models cannot be broken and do not require physical storage space, an important consideration given the legal requirements for maintaining patient records. (Camardella et al. 2017b; Brown et al. 2018). The digital model can also be manipulated using computer software to design crowns, bridges, inlays, dentures, implants

guides, etc. Following the digital design, these products can then be machined from a ceramic block, when appropriate (Alghazzawi 2016).

This process has proven a very useful application in prosthodontics. Specifically, in the case of crown and bridge work, CAD/CAM technology has allowed for same-day-crowns, reducing the need for temporary crowns and additional appointments. However, milling and other subtractive manufacturing processes have their limitations and disadvantages. It may result in substantial amounts of waste, as the left-over material cannot be reused and must be discarded. Another limitation of milling is that the accuracy of the object is dependent on the complexity of the object and the size of the milling tool (Dawood et al. 2015). This is demonstrated by the fact that when the thinnest part of the object being milled is smaller than the size of the bur that is cutting it, then the object will be over milled, possibly resulting poor fit of a dental restoration (Alghazzawi 2016).

A disadvantage of the all-digital workflow is, ironically, the lack of a physical model. Though there are several advantages to the digital workflow, and digital models in particular, there are still some applications in dentistry where a physical model and a physical workflow is best or even necessary. Some orthodontic appliances, such as functional appliances, rapid palatal expanders, and aligners still require the use of a physical model (Camardella et al. 2017a; Brown et al. 2018). This is in part because there currently is not a suitable material for directly printed aligners, and directly printing metal appliances is costly and requires extensive post processing (Dawood et al. 2015; Williams et al. 2022). Additionally, the ability to hold the model in hand is sometimes preferred for patient presentation or education. Additive manufacturing overcomes some of these limitations that are inherent to both milling and an all-digital workflow (Brown et al. 2018).

## **Additive Manufacturing in Dentistry**

Similar to subtractive manufacturing processes in the dental field, additive manufacturing utilizes CAD technology in the scanning and designing phases of the workflow. Then, instead of milling from a block, additive manufacturing builds the object layer by layer from the 3D model data. When compared with subtractive manufacturing, it has the potential to yield finer detail in scenarios where there are undercuts or complex geometric shapes. Additive manufacturing also produces less waste, is faster, and allows for larger and more customized products. Though 3D printing still has some limitations in regard to what kind of materials can be used, it is a technology that has vast implications in the field of dentistry (Alghazzawi 2016).

Additive manufacturing is already being used in many aspects of clinical dentistry and maxillofacial surgery, in some cases providing enhanced treatment planning options that were previously impossible. For example, oral and maxillofacial surgeons can obtain a digital 3D reconstruction of a patient's jaws, 3D print this model, and simulate the surgical procedure before ever making an incision. Additionally, additive manufacturing has been used to directly print implant placement guides, complete dentures, partial denture frameworks, occlusal splints and mouthguards. There is a host of applications that is transforming the workflow for the manufacture of dental devices and appliances (Dawood et al. 2015).

## **Additive Manufacturing in Orthodontics**

The specialty of orthodontics has already adopted various applications of 3D printing. This technology has been used to print orthodontic retainers, indirect bonding guides, as well as palatal expanders (Dawood et al. 2015). Even directly printing orthodontic brackets is

being explored (Oberoi et al. 2018). Perhaps the most extensive way additive manufacturing is used in orthodontics is related to the use of 3D-printed orthodontic models in clear aligner fabrication.

The process of producing clear aligners begins with a digital scan of a patient's teeth, followed by manipulation of the digital model (using CAD technology) to create multiple stages of tooth movement. Then each of these stages is printed as a part of a set of solid dental models, printed in a horseshoe shape, lying flat on the platform with the occlusal plane facing up (fig. 1A). These models are then used to create a series of thermoformed plastic trays (fig 1B) that the patient wears in sequence to achieve the desired tooth movement. For example, a treatment of a relatively simple malocclusion lasting fourteen months, with 2 trays (upper and lower) changed every two weeks, will require over fifty trays to complete the treatment (Gay et al. 2017).

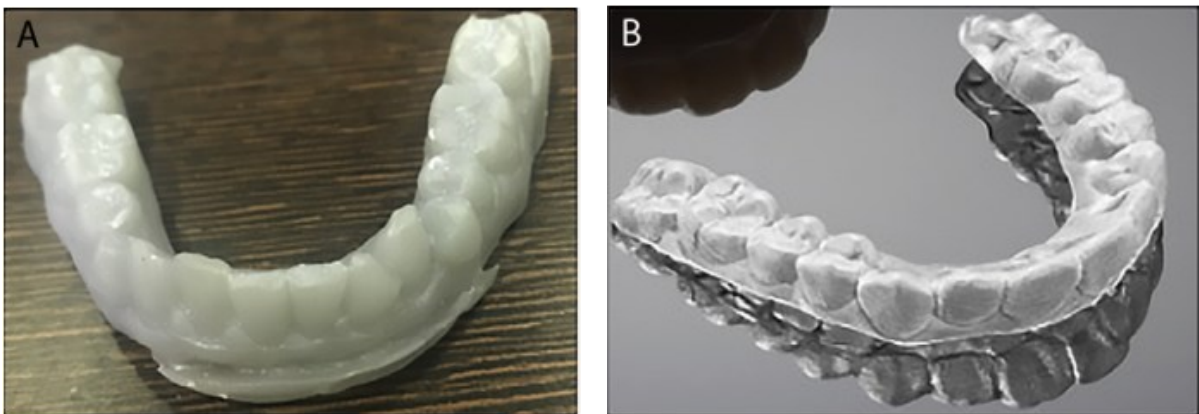


Figure 1. 3D-printed orthodontic model and thermoformed clear aligner. A. solid, horseshoe shaped model with occlusal plane facing up. B. thermoformed clear aligner made from a 3D-printed model.

Historically, the 3D printing and fabrication of aligners has been done on a large scale by commercial dental laboratories or 3D printing companies. However, there has been a recent shift of these processes taking place completely in private dental/orthodontic offices. This change in venue of fabrication has the potential to introduce more variation in the printing process. Introducing more variability into the process requires a more thorough evaluation of the factors that affect accuracy of 3D printing. A lack of accuracy will have a direct effect on the fit of the aligner and thus, the quality of treatment that the patient receives (Camardella et al. 2017b). Therefore, factors influencing accuracy must be adequately understood by those who choose to incorporate this technology into patient treatment.

### **Factors Influencing Accuracy in 3D-Printing in Orthodontic Applications**

As more orthodontists incorporate additive manufacturing into their practice, the accuracy of this technology must be evaluated to ensure the highest level of patient care. First, there should be a certain degree of confidence that the scanning process is accurate, and substantial inaccuracies are not being introduced into the workflow before 3D printing is even started. Fortunately, the scanning technology has been the subject of extensive research and studies show that digital scans can in fact accurately reproduce the intraoral structures as a digital model (Brown et al. 2018; Medina-Sotomayor et al. 2018). With confidence that the scanning step is reliable, the actual 3D printing process and outcomes of that process should be evaluated.

When evaluating whether the 3D printing process is accurate enough to be used for its desired application, parameters of accuracy should be defined. More specifically, for the object of this study, the degree of accuracy of the 3D-printed orthodontic model should be

defined. It is important to note that different dental processes require different levels of accuracy. For example, studies that investigated the fit of 3D-printed full-coverage crowns set parameters at 0.1 mm to evaluate the fit of the restoration i.e. marginal gap, meaning that any deviation of more than 0.1 mm from the master model was said to be outside the range of clinical acceptability (Osman et al. 2017; Rungrojwittayakul et al. 2020). For orthodontic models, the evaluation is related to how well the model duplicates the dimensions of the patient or master model. For these comparisons, some studies suggest that any deviation less than  $\pm 0.5$  mm is considered clinically acceptable (Camardella et al. 2017a; Sherman et al. 2020). However, the purposes for which many 3D-printed orthodontic models are used currently require an even higher degree of accuracy. Specifically, for clear aligner fabrication an absolute deviation of more than  $\pm 0.25$  mm is unacceptable for fabrication of an active appliance (Short et al. 2018; Williams et al. 2022). Maximum tooth movement for each clear aligner ranges from 0.25 to 0.3 mm, so it stands to reason that deviations in accuracy outside of this range would lack clinical efficacy (Kim et al. 2018). In addition, cross arch measurements could have a larger range for error of  $\pm 0.5$  mm, as 2 teeth are included in the measurement.

Utilizing the determined parameters for clinical acceptability, researchers are evaluating how variations in the printing process affect the accuracy of the models. Printer type, layer thickness, build angle, and model body type are some of the factors that have an impact on accuracy and clinical acceptability of 3D-printed orthodontic models.

### **Type of Printer**

While the type of printer will vary depending on the application, in orthodontics, the most common 3D printer types are the stereolithography apparatus (SLA) and digital light



processing (DLP). Both SLA and DLP, while used in commercial dental laboratories, have gained popularity in orthodontic offices due to the ability to have a “desktop printer” that does not take up a lot of space, is relatively inexpensive, and prints relatively quickly and accurately (Zhang et al. 2019). Both technologies utilize photopolymers in a vat, the floor of which is transparent. A platform is lowered into the vat typically within 50-100  $\mu\text{m}$  of the transparent floor. Next, a light source cures the polymer that is between the platform and the floor, after which the platform rises slightly to allow another layer of liquid photopolymer to flow between the floor and previously cured layer. Another layer is cured and the process continues (Dawood et al. 2015). The difference between the SLA and DLP lies in the light source. SLA printers use a laser that moves along the contour of the object, where DLP printers cure the entire layer at one time with a high-resolution light projector (Choi et al. 2019). Though these processes are similar, they are different enough to have drawn attention of researchers to determine whether they are both adequately accurate to be used for orthodontic applications.

Several studies have been conducted to determine the accuracy of DLP and SLA printers. Researchers have investigated tooth size in three dimensions, arch width, arch length, and occlusion. Multiple studies have shown statistically significant differences in the accuracy of SLA vs. DLP printers. However, the statistically significant differences rarely translated into clinical significance when compared to the 0.25 mm acceptable deviation that was discussed earlier. It is also important to note that the studies comparing the printer types had to consider other variables, so the models were mostly printed as a solid body type, in horseshoe shape (important 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 reasonably sufficient evidence to suggest that both DLP and SLA printers can be used to 3D print orthodontic models that are sufficiently accurate to be used for clinical applications.

### **Print Layer Thickness**

Print resolution, like the idea of pixel size in photography, is an important variable in additive manufacturing. The Z-axis of print resolution is based on the thickness of each layer that is cured as the platform rises. This layer tends to range from about 20 to 100  $\mu\text{m}$  in thickness. This variable has particular importance because it is a setting that can be changed by the operator, and it is likely to be changed since thicker layers mean fewer layers, and consequently shorter print times. The question is whether changing layer thickness has an impact on the clinical accuracy of the printed model. Similar to studies evaluating printer type, the research regarding layer thickness shows some statistical variability when print layer thickness is adjusted, but the variation still falls within the accepted range of clinical accuracy. That being said, there is evidence to suggest that for certain DLP printers, the 50  $\mu\text{m}$  layer thickness yields a higher degree of accuracy and should be used when the highest degree of accuracy is needed (Loflin et al. 2019; Zhang et al. 2019).

### **Effect of Build Angle on 3D-Printed Orthodontic Models**

Like layer-thickness, build angle is a variable that can be manipulated by the operator to improve efficiency. For example, models printed lying flat on the platform take up far more room on the platform than models in the vertical position. When trying to print large batches, it may be advantageous to print in orientations other than horizontal in order to print more at one time. Despite improved efficiency with varying build angles, the angle at which an object is 3D-printed has been shown in various studies to have an impact on the accuracy

of the printed object. For example, a study that compared the accuracy of 3D-printed crowns suggests that there is a build angle that optimizes accuracy and fit of the finished restoration (Alharbi et al. 2016). Shim et al. came to the same conclusion in a study evaluating accuracy of a printed block (2019).

Few studies have addressed the question of build angle as it relates to accuracy of orthodontic models (Short et al. 2018; Ko et al. 2021). One study utilized an SLA printer to print the models as a solid, horseshoe shape, and tested three orientations: flat (0°), 20°, and perpendicular (90°) (fig. 2). The researchers found that all three types, on average, were within the range for clinical acceptance ( $\pm 0.25\text{mm}$ ).

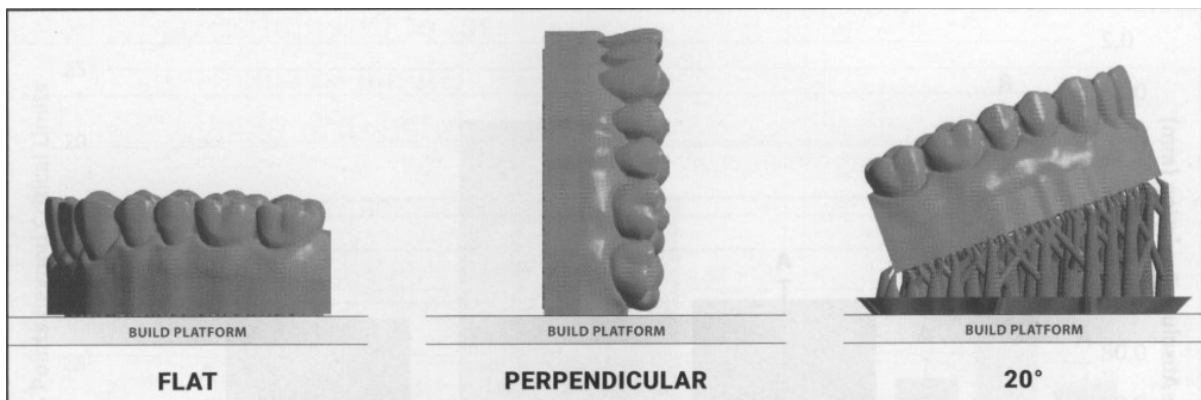


Figure 2. Build angles investigated by Short et al. 2018

However, when analyzing the precision of each measured value, the perpendicular model had 20 % of its measurements outside the range of clinical acceptance compared to less than 5% of the other two orientations (Short et al. 2018). This study was instrumental in opening the discussion on build angles for orthodontic models. Yet, more needs to be done in

order to verify and extend the information available. For example, will the use of a DLP printer have the same issues? Will it be more accurate, or just inaccurate in a different way? Is there a build angle at which the models remain accurate, but still allow for more efficient production via more models on the platform? The effect that build angle has on the accuracy of the 3D-printed orthodontic models, specifically using DLP technology, is an area of research that needs additional exploration.

### **Model Body Type: Shell vs Solid**

Another way that the additive manufacturing technique can be modified for less material use is by changing the design of the model body. A number of studies have verified that certain SLA and DLP printers print with sufficient accuracy to be used for fabrication of clear aligners when the model is solid, horseshoe-shaped, and has a cross bar linking the posterior segments (Camardella et al. 2017a; Gay et al. 2017; Brown et al. 2018; Zhang et al. 2019; Rungrojwittayakul et al. 2020; Sherman et al. 2020). The accuracy of a horseshoe-shaped model is important because this is the form the model must take in order to be used in clear aligner fabrication.

Orthodontic models can further be modified by printing them as a hollow shell rather than a solid object. This modification has the potential to drastically reduce the amount of material that is used per model, and at least for the SLA printers, also significantly decrease build time. Both material use and processing time are important considerations especially when manufacturing large numbers of models. Although this area is lacking extensive research, some have suggested that as long as the shell is no less than two millimeters thick, then it maintains its accuracy when compared with its solid counterpart (Kenning 2020; Rungrojwittayakul et al. 2020). These studies, however, do not investigate whether these

hollow models maintain accuracy when printed at different angles. If an orthodontic model can be printed in a vertical position as a hollow shell, the resultant decrease in material and increase in production could have favorable implications for orthodontists who desire to make 3D printing a more extensive part of their practice.

### **Problem Statement**

Multiple studies have shown that the printers most commonly used in dentistry (SLA and DLP) are able to accurately print clinically acceptable orthodontic models when printed according to manufacturing recommendation. As already mentioned, there are, however, several ways operators of these devices can change the settings to enhance production efficiency and minimize waste, including modifying layer thickness and build angle, and printing the model as a hollow shell. The literature, to date, provides useful information regarding model accuracy and print layer thickness, but build angle and model body type are variables that have not yet received adequate attention in relation to resultant model accuracy. While two studies have investigated the accuracy of orthodontic models as affected by build angle (Short et al. 2018; Ko et al. 2021), none have addressed the issue with the specific non-industrial DLP printer used in this study, which, if reliable, can be reasonably utilized in private practice. Similarly, two studies suggested that models produced as a hollow shell are accurate as long as they are 2 mm thick (Kenning 2020; Rungrojwittayakul et al. 2020). However, it has not been determined if a hollow shell built at varying angles maintains acceptable accuracy. In short, the purpose of this study will be to compare whether 3D-printed models, manufactured using a desktop DLP printer, maintain clinically acceptable levels of accuracy when produced as a hollow shell or a solid model and at varying build angles.

## **Hypothesis**

1. The accuracy of 3D-printed orthodontic models will vary as a function of the build angle and model body type (shell versus solid) when compared with selected values of clinical relevance ( $\pm 0.25$  mm for individual tooth measurements and  $\pm 0.5$  mm for cross arch measurements).

## CHAPTER 2

### MATERIALS AND METHODS

#### **Developing the Master Model**

To develop the master model, a vinyl polysiloxane<sup>1</sup> (VPS) impression was obtained from the maxillary arch of an ideal typodont<sup>2</sup>. The 3<sup>rd</sup> molars were removed from the typodont to better represent the more common clinical scenario encountered with digital scans. Next, vacuum<sup>3</sup> mixed type III stone<sup>4</sup> was poured into the set VPS impression, allowed to set, then cleaned and trimmed. Then a scan of the stone model was acquired using an intraoral scanner<sup>5</sup>. The stone model was scanned instead of the typodont due to problems encountered with glare off the shiny surface of the typodont.

The STL file obtained from the model scan was uploaded into Meshmixer<sup>6</sup> software, where the model was manipulated in preparation for 3D printing. These manipulations included addition of a crossbar linking the posterior segments to ensure better arch width integrity (Camardella et al. 2017a) and raised 2x2x1 mm prisms, or reference cubes, from which several of the measurements were made. Once the digital model had the necessary modifications, it was saved and maintained as the digital master model (fig. 3).

---

<sup>1</sup> Aquasil Ultra Monophase, Dentsply Sirona, 13320 Ballantyne Corporate Place, Charlotte, NC 28277

<sup>2</sup> Kilgore, NISSIN 200 Type, Kilgore International, Inc., 595 W Chicago St, Coldwater, MI 49036

<sup>3</sup> Whipmix Vacuum Power Mixer Plus, 361 Farmington Ave, Louisville, KY 40217

<sup>4</sup> Pemstone Golden, Garreco LLC, 430 Hiram Rd., Heber Springs, AR 72543

<sup>5</sup> Itero Element II, Align Technology, Ltd., 3 Ariel Sharon Blvd, Or Yehuda, Israel

<sup>6</sup> Autodesk Meshmixer, Autodesk Inc., 111 McInnis Parkway San Rafael, CA 94903

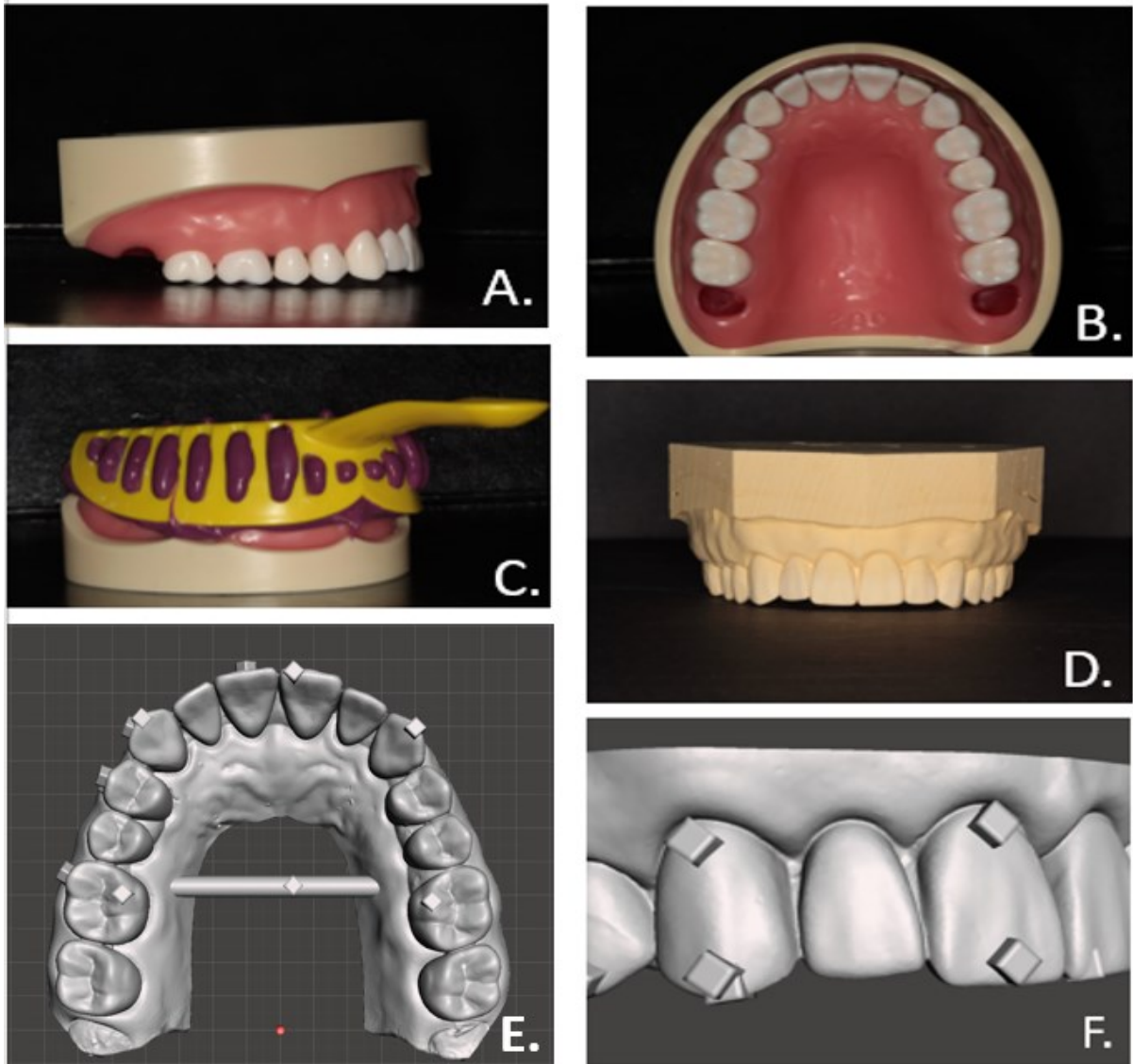


Figure 3. Stages of digital master model development. A. Posterior buccal view of ideal maxillary typodont with 3<sup>rd</sup> molars removed. B. Occlusal view of ideal maxillary typodont with 3<sup>rd</sup> molars removed. C. VPS impression of typodont. D. Stone model of ideal typodont. E. Occlusal view of digital master model. F. Zoomed in view of reference cubes on digital master model.



### 3D Printing of the Experimental Models

Following master model development, the digital master model file was used as the source for printing experimental models that were printed as either a solid model or as a shell. In addition, the solid and shell experimental models were printed using the following print angles: 0° (horizontal); 70°; and 90° (vertical) (fig. 4). Each experimental model type (shell-0°, -70°, -90°; solid-0°, -70°, -90°) (Figure 5) was printed ten times, with a total sample of sixty models.

The experimental models were printed using a photosensitive polymer<sup>7</sup> with a calibrated benchtop DLP printer<sup>8</sup>. The printer was set to print with a layer thickness of 100 µm, which is consistent with the goal of increased speed and efficiency sought out by the practicing orthodontist. The models printed as a shell had a shell thickness of 2 mm, which had previously been determined to provide adequate dimensional accuracy (Kenning 2020; Rungrojwittayakul et al. 2020).

The 0°-shell model was also printed with vents on the distal surface to allow uncured resin to escape during printing. Each print batch included one of each of the six experimental model types to account for possible batch errors. In addition, each batch had the models arranged differently on the platform to minimize error from possible differences from different positions on the platform (Sherman et al. 2020). After printing the experimental models, manufacturer recommendations were followed for post processing including rinsing the models with 99% isopropyl alcohol (IPA), then placing in an ultrasonic cleaner<sup>9</sup> for 5

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<sup>7</sup> Die and Model Tan, SprintRay, 20321 Valencia Cir, Lake Forest, CA 92630

<sup>8</sup> Sprintray Pro, SprintRay, 20321 Valencia Cir, Lake Forest, CA 92630

<sup>9</sup> Vevor, 9448 Richmond Pl E, Rancho Cucamonga, CA 91730

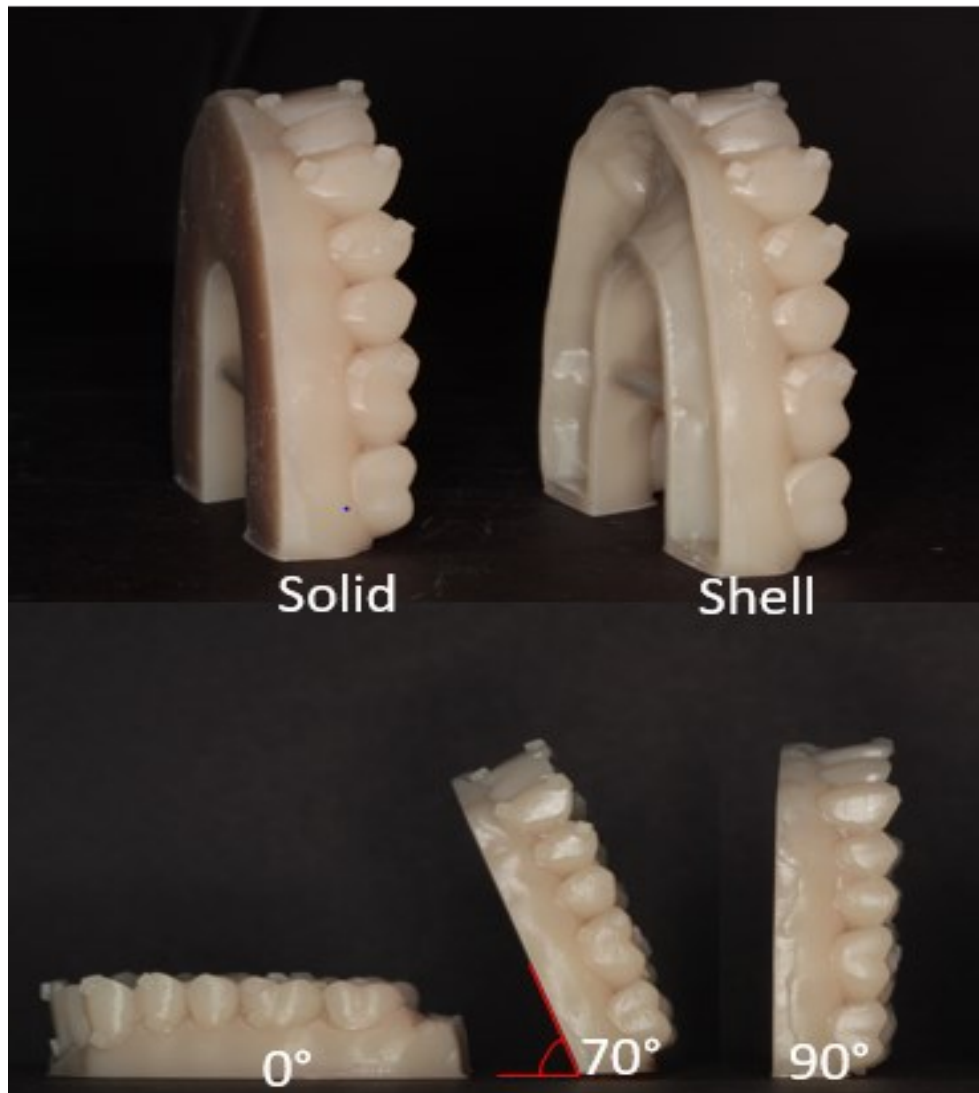


Figure 4. Model body types and print angulations: solid and shell; three angles at which the models were printed (0°, 70°, and 90°).

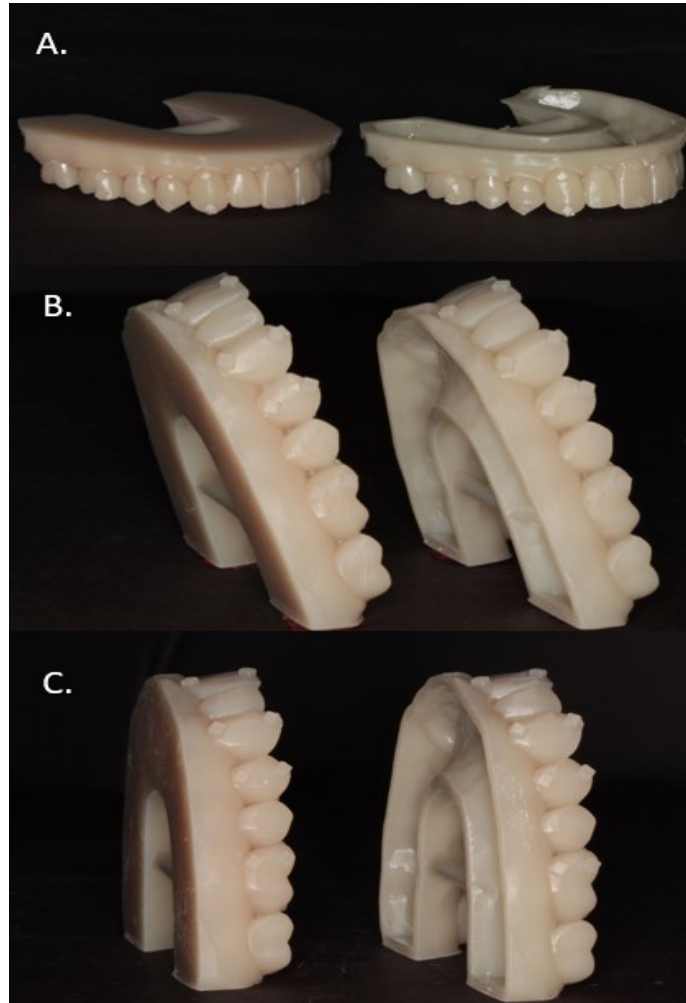


Figure 5. Six types of models printed: A. 0° solid and shell. B. 70° solid and shell. C. 90° solid and shell.

minutes. Then the models were air dried with forced air and post cured in the blue-light convection oven<sup>10</sup> for 15 minutes. After post processing, the models were labeled with a specimen ID that was used during the measuring process.

### **Measuring the Digital Master Model**

The digital master model was measured using the same software program used to create and modify the digital master model<sup>11</sup>. The majority of the measurements were made from the center of the reference cubes described previously in the section “Developing the Master Model.” The center of each cube was found using a transparent plastic sheet<sup>12</sup> with perpendicular crosshairs drawn onto the sheet. The transparent sheet was laid over the computer screen with the four arms of the crosshairs bisecting each of the four corners of the reference cube (fig. 6). This method was used instead of measuring from a point angle on the reference cubes, as some of the point angles are not fully printed in some print angulations.

There was a total of eleven measurements obtained on the master model (fig. 7). For all tooth width measurements, reference cubes were not used and instead, measurements were made from the interproximal contact points, as this landmark was easily and repeatedly identifiable on both the digital master model and experimental models.

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<sup>10</sup> Pro Cure, SprintRay, 20321 Valencia Cir, Lake Forest, CA 92630

<sup>11</sup> Autodesk Meshmixer, Autodesk Inc., 111 McInnis Parkway, San Rafael, CA 94903

<sup>12</sup> Clipco Dry Erase Pocket Sleeves, Trade Quest Global Corp., 7360 NW 34<sup>th</sup> St., Miami, FL 33122

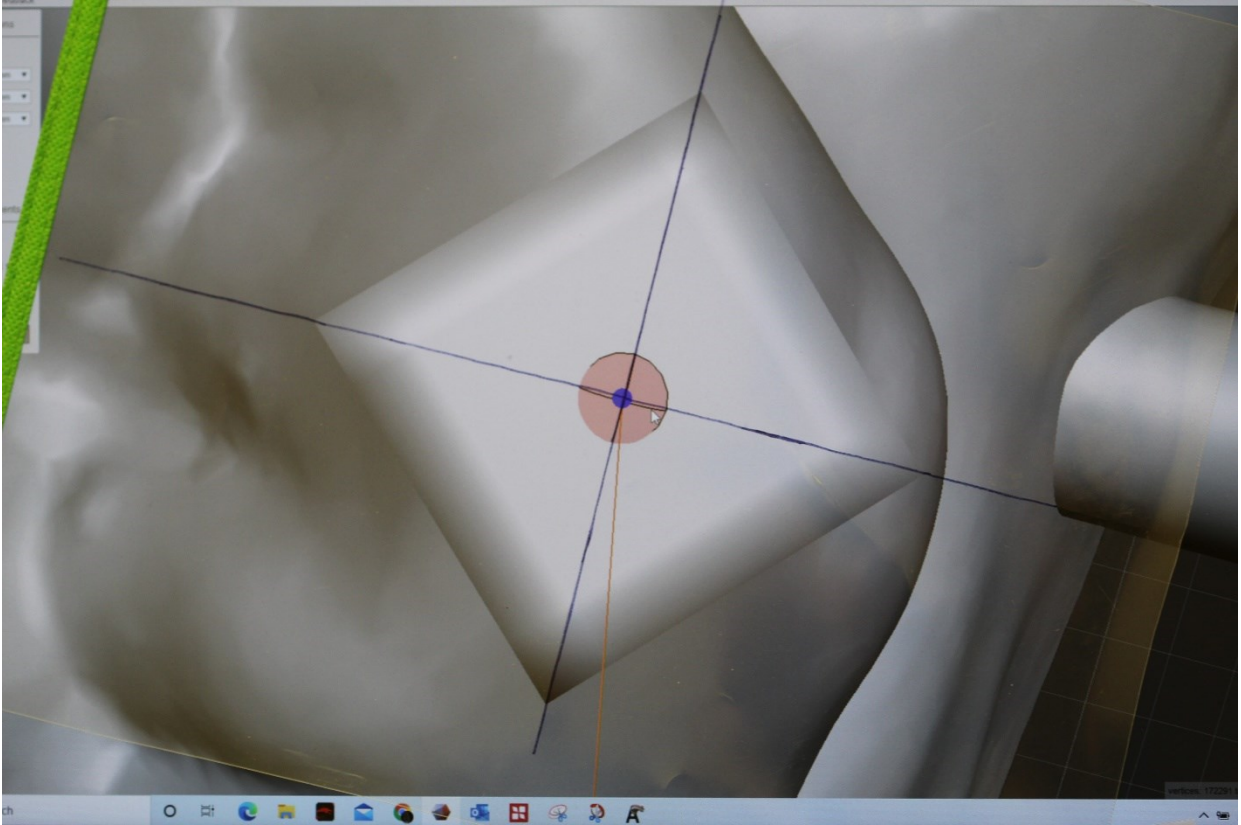


Figure 6. Center of the reference cube (digital master model). Transparency with crosshairs laid over the computer screen with arms of crosshairs bisecting the four corners of the cube.

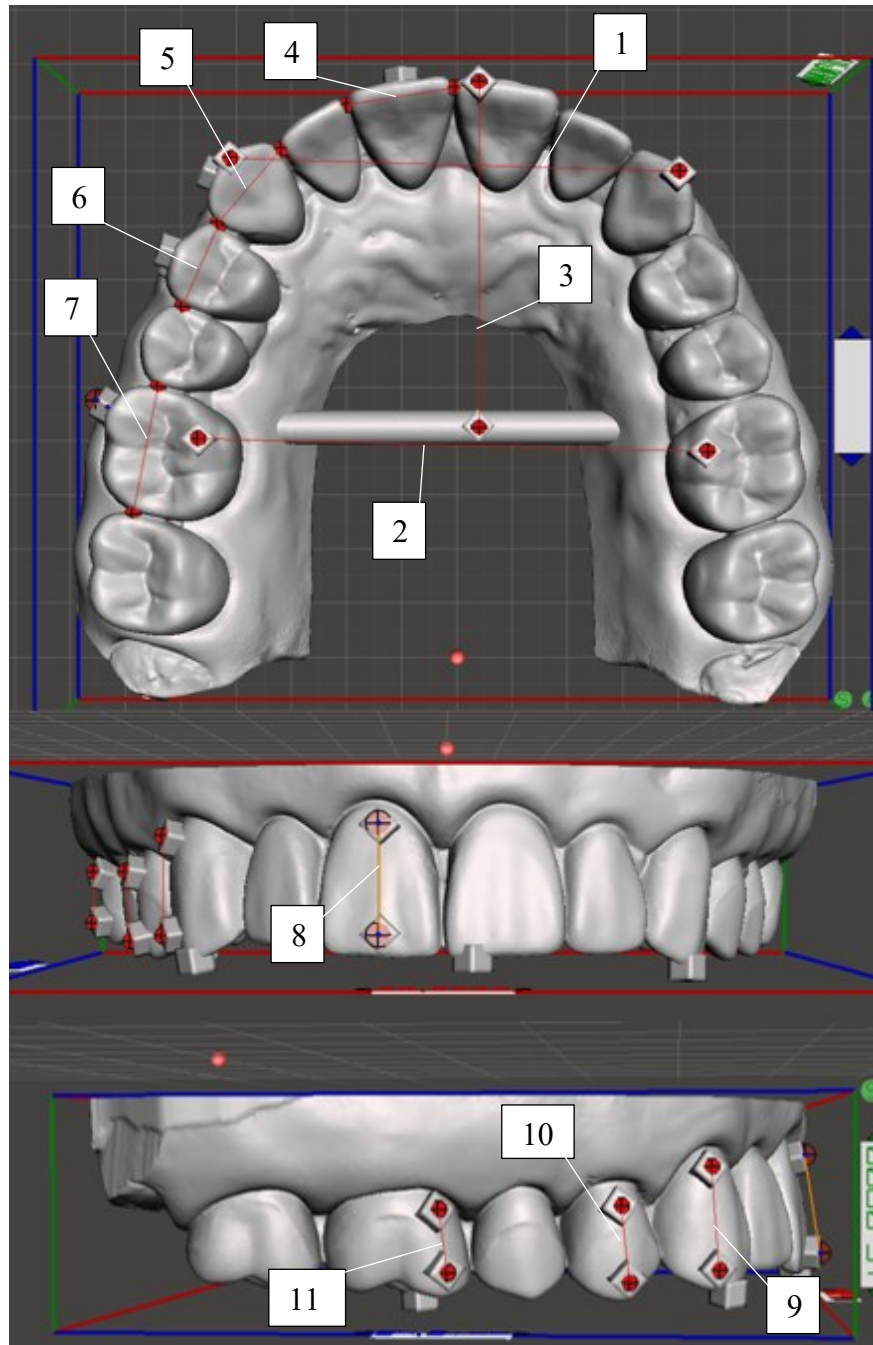


Figure 7. Measurements on the digital master model: 1. intercanine distance 2. intermolar distance 3. anteroposterior arch depth 4. central incisor width 5. canine width 6. premolar width 7. molar width 8. central incisor height 9. canine height 10. premolar height 11. molar height.

### Measuring the Printed Experimental Models

Following master model measurements, the experimental models were measured in a randomized order using a measuring microscope<sup>13</sup> with a level of accuracy of 0.01 mm. The measuring microscope was synced with a monitor<sup>14</sup>, crosshair generator<sup>15</sup>, and a digital readout system<sup>16</sup>. The same measurement protocol was used for the digital master model that was used for the experimental models. Model holders, or jigs, were used to stabilize and provide reproducibility of the model orientation on the measuring microscope platform. Each of the six model types required three jigs; one to hold the model with the occlusal plane in view, one for the anterior facial view, and one for the posterior buccal view (fig. 8). The jigs

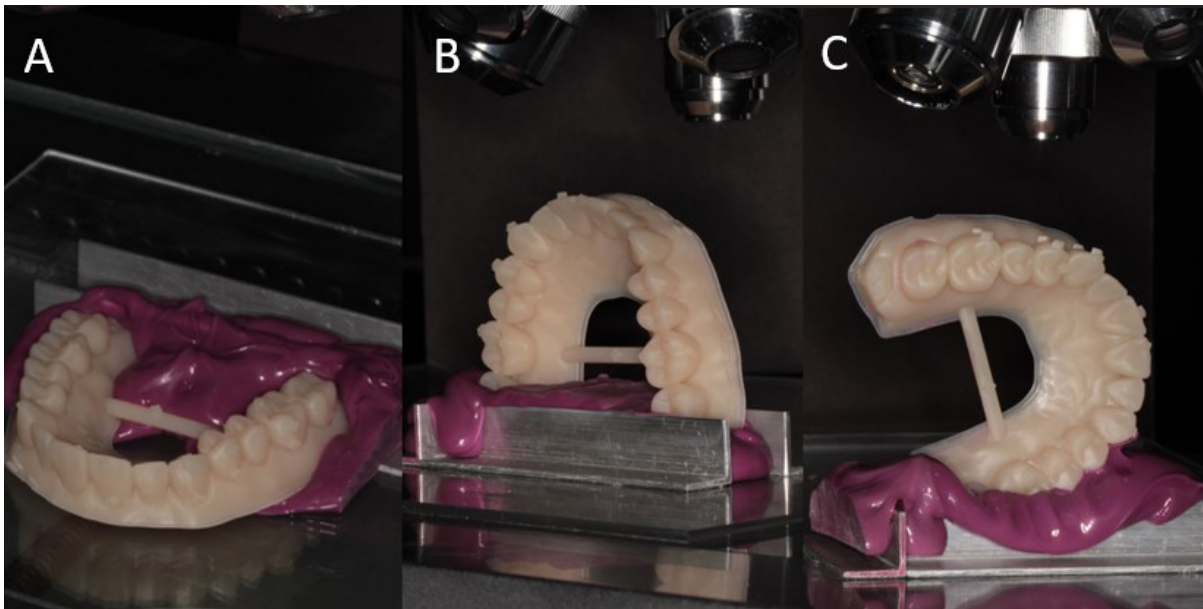


Figure 8. Models mounted on the microscope platform: A. Solid-0° model mounted to view the occlusal surface. B. Solid-0° model mounted to view the anterior labial surfaces. C. Solid-0° model mounted to view the posterior right buccal surfaces.

<sup>13</sup> Nikon Measurescope MM-22 with 7VL stage, 1300 Walt Whitman Rd, Melville, NY 11747

<sup>14</sup> Sony Corporation of America, 550 Madison Avenue, New York, NY 10022 – 3211

<sup>15</sup> Techniquip DCG-100A, 530 Boulder Ct Ste 103, Pleasanton, CA 94566

<sup>16</sup> Quadra-Chek 200, Metronics, Inc., 710 Medtronic Pkwy, Minneapolis, MN 55432

were made using VPS and were placed on a removable platform. The platform had metal brackets superglued to the surface which served as a reference structure for the side of the jig resting on the platform. With the jigs completed, the models were measured under the measuring microscope, utilizing the same reference points as the master model but this time on the printed experimental models (fig. 9). The same transparent sheet was laid over the microscope display monitor to find the centers of the reference cubes (fig. 10). Due to the digital readout system reporting distances in the x, y, and z axes independently and not a true total distance, data was placed into data analysis software<sup>17</sup> to determine actual distance using the Pythagorean theorem. For each measure, the difference between the master model and the experimental model was calculated in millimeters.

All measurements of the digital master model and experimental models were performed by one investigator. Before experimental data collection began, a measuring calibration was performed for the measurements on the digital master model and for randomly selected measurements across the experimental models. The same measurements were done on multiple days to assure intra-rater reliability as demonstrated by minimal variability between measurement sessions. All repeated measurements from the three time-points of the calibration fell within a range of 0.1 mm.

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<sup>17</sup> Microsoft Excel, 1 Microsoft Way, Redmond, WA 98052



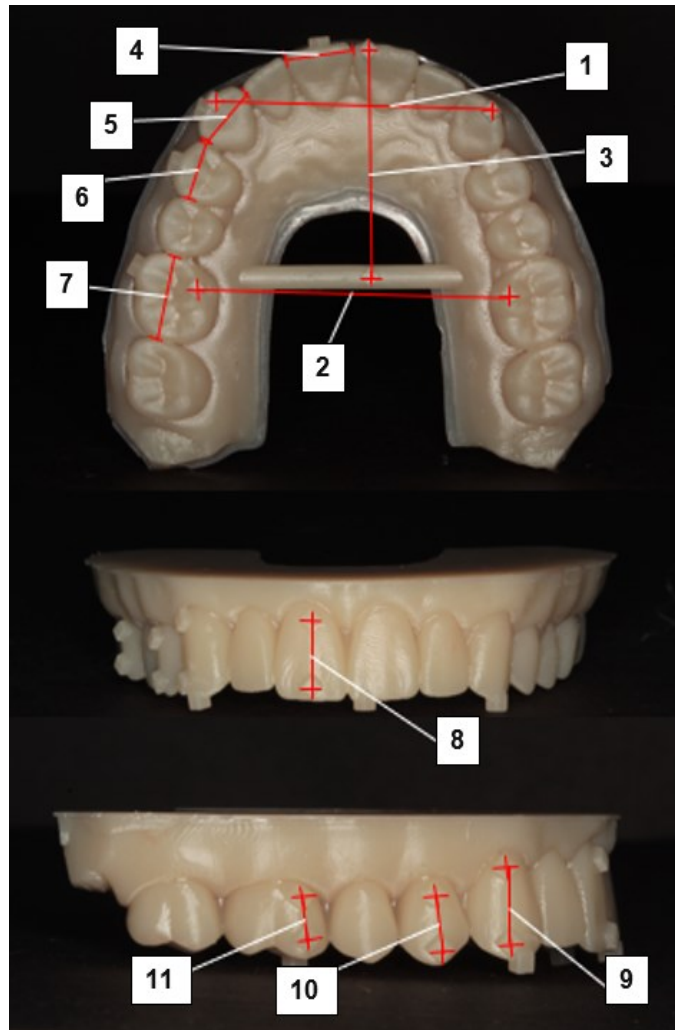


Figure 9. Measurements on the printed models: 1. Intercanine distance 2. Intermolar distance 3. Anteroposterior Arch Depth 4. Central incisor width 5. Canine width 6. Premolar Width 7. Molar width 8. Central Incisor height 9. Canine height 10. Premolar Height 11. Molar height.

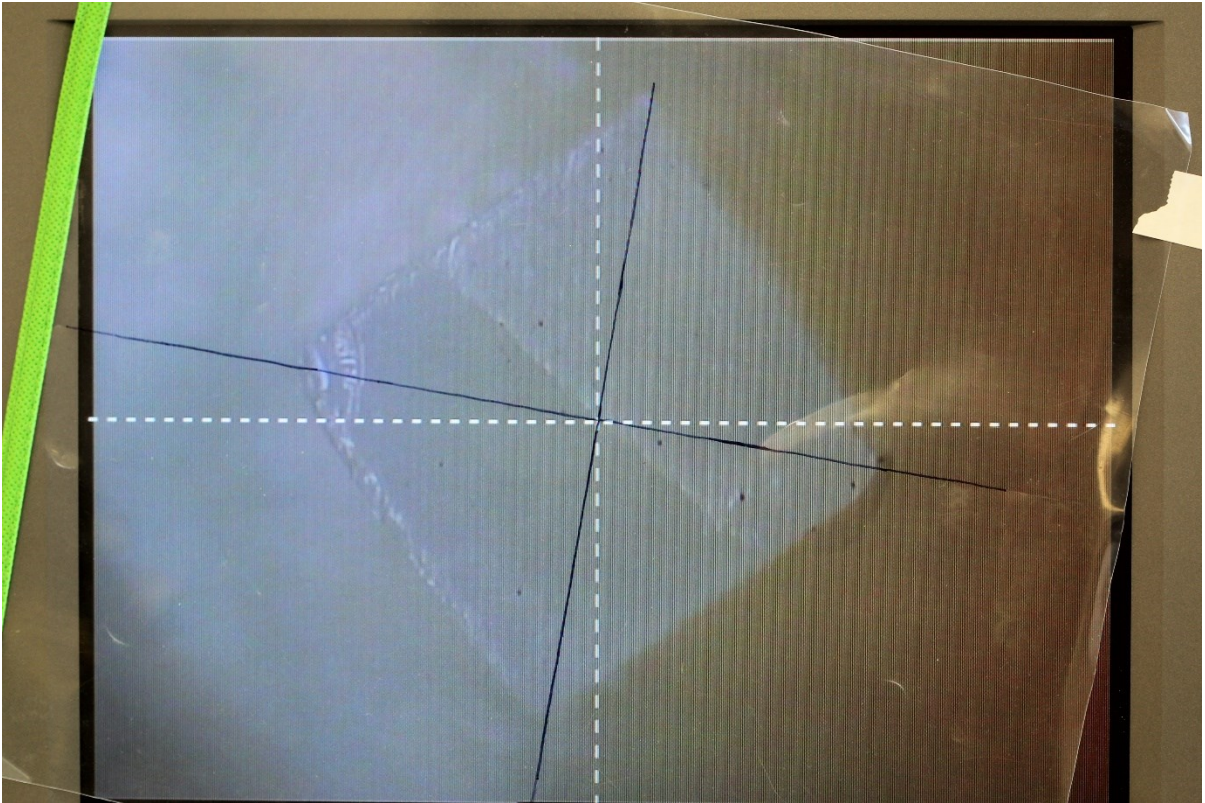


Figure 10. Center of the reference cube (printed model). Transparency with crosshairs laid over the microscope display monitor with arms of crosshairs bisecting the four corners of the cube.

## **Experimental Design**

This experiment was a laboratory study that used a two-factor, repeated measures design. The first independent variable was the body type of the experimental printed model: solid or shell. The second independent variable was the angle at which the model was printed relative to the printing platform. The print angles were 0° (horizontal), 70°, and 90° (vertical). The dependent variable was a defined set of measurements representing tooth height, tooth width, intercanine distance, intermolar distance, and anteroposterior arch depth (table 1).

The sample included a total of 60 specimens made up of six groups and ten printed models in each of those groups. The six groups were as follows: solid-0°, solid-70°, solid-90°, shell-0°, shell-70°, and shell-90°.

## **Data Analysis**

Data analysis included an evaluation of mean measures of the experimental models as they compared to the digital master model. The mean values were assessed for clinical acceptability based on the clinically acceptable parameters being used in this study. Mean measures were considered clinically acceptable if they did not vary more than  $\pm 0.25$  mm for individual tooth measurements or  $\pm 0.5$  mm for cross arch measurements. In addition to the mean measures, the raw data was evaluated to determine how many data points fell outside the respective selected range of clinical acceptability.

TABLE 1  
EXPERIMENTAL DESIGN

Independent Variables		Dependent Variables										
Model Groups (10/group)		Intra-tooth measurements								Inter-tooth measurements		
		Width (mm)				Height (mm)				Length (mm)		
Model Type	Print Angle	I	C	P	M	I	C	P	M	ICD	IMD	APAD
Solid	0°											
	70°											
	90°											
Shell	0°											
	70°											
	90°											

Abbreviations: central incisor (I), canine (C), 1<sup>st</sup> premolar (P), and 1<sup>st</sup> molar (M), intercanine distance (ICD), intermolar distance (IMD), and anteroposterior arch depth (APAD).

## CHAPTER 3

### RESULTS

Mean differences and standard deviations of experimental models vs the digital master model are presented in table 2. Of all the mean intra-tooth measurements, only the canine height for the 0° shell model had a mean difference ( $-0.26 \text{ mm} \pm 0.03$ ) that fell outside the range of clinical acceptability ( $\pm 0.25 \text{ mm}$ ). It was also observed that for all intra-tooth measurements, the standard deviations were within 0.07 mm. For mean inter-tooth measurements, while none were beyond the range of acceptability ( $\pm 0.5 \text{ mm}$ ), the standard deviations were larger ranging from 0.04 to 0.30 mm.

The number of raw measurements that fell outside the range of clinical acceptability are reported in table 3. A total of 660 individual measurements were recorded. Of those, only fifteen had differences outside the clinically acceptable range (table 3). Thus, 98% of the raw measurements fell within the selected range of clinical accuracy. For seven of the eleven measured structures and distances, all raw measurements were clinically acceptable across 60 experimental models. The following four structures showed clinically unacceptable measurements in some cases: Intermolar distance (4/60), molar crown height (1/60), canine crown height (9/60), and central incisor crown height (1/60).

The 70° solid and 90° solid models were the only models that did not have any data points outside the range of clinical acceptability. It was also noted that all sixty experimental models had crown height measurements less than the digital master model, suggesting that all the crowns were shorter, regardless of the model body type or print angle.

In summary, the hypothesis was not supported, since overall model clinical accuracy was not impacted as a function of model type or print angle.

TABLE 2

## MEAN MEASUREMENTS (mm) OF EXPERIMENTAL MODELS

Model type	Solid				Shell					
	0°	70°	90°	0°	70°	90°	0°	70°	90°	
Print angle										
Incisor Height	-0.20 ± 0.03	-0.09 ± 0.04	-0.08 ± 0.06	-0.23 ± 0.03	-0.10 ± 0.04	-0.08 ± 0.06	-0.10 ± 0.04	-0.10 ± 0.04	-0.08 ± 0.06	
Canine Height	-0.25 ± 0.03	-0.14 ± 0.05	-0.14 ± 0.04	-0.26 ± 0.03*	-0.19 ± 0.03	-0.14 ± 0.04	-0.19 ± 0.03	-0.19 ± 0.03	-0.14 ± 0.04	
Premolar Height	-0.20 ± 0.02	-0.12 ± 0.03	-0.14 ± 0.04	-0.21 ± 0.03	-0.14 ± 0.06	-0.12 ± 0.04	-0.14 ± 0.06	-0.14 ± 0.06	-0.12 ± 0.04	
Molar Height	-0.19 ± 0.02	-0.01 ± 0.04	-0.12 ± 0.05	-0.19 ± 0.05	-0.13 ± 0.05	-0.10 ± 0.02	-0.13 ± 0.05	-0.13 ± 0.05	-0.10 ± 0.02	
Incisor Width	-0.04 ± 0.05	-0.01 ± 0.04	-0.03 ± 0.06	-0.03 ± 0.05	-0.02 ± 0.05	-0.09 ± 0.07	-0.02 ± 0.05	-0.02 ± 0.05	-0.09 ± 0.07	
Canine Width	0.04 ± 0.05	0.01 ± 0.04	-0.02 ± 0.03	0.04 ± 0.04	0.01 ± 0.03	-0.05 ± 0.03	0.01 ± 0.03	0.01 ± 0.03	-0.05 ± 0.03	
Premolar Width	-0.02 ± 0.03	-0.02 ± 0.04	-0.02 ± 0.03	-0.03 ± 0.04	-0.04 ± 0.03	-0.02 ± 0.03	-0.04 ± 0.03	-0.04 ± 0.03	-0.02 ± 0.03	
Molar Width	0.02 ± 0.04	0.01 ± 0.03	0.03 ± 0.01	0.01 ± 0.05	-0.02 ± 0.02	-0.01 ± 0.02	0.01 ± 0.05	-0.02 ± 0.02	-0.01 ± 0.02	
Intermolar Width	-0.15 ± 0.25	0.10 ± 0.23	0.13 ± 0.25	0.09 ± 0.27	0.37 ± 0.17	0.12 ± 0.30	0.09 ± 0.27	0.37 ± 0.17	0.12 ± 0.30	
Intercanine Width	-0.04 ± 0.20	-0.07 ± 0.19	-0.07 ± 0.22	0.01 ± 0.24	0.07 ± 0.13	-0.21 ± 0.25	0.01 ± 0.24	0.07 ± 0.13	-0.21 ± 0.25	
Arch Depth	-0.18 ± 0.08	-0.15 ± 0.05	-0.17 ± 0.06	-0.22 ± 0.12	-0.21 ± 0.06	-0.26 ± 0.04	-0.22 ± 0.12	-0.21 ± 0.06	-0.26 ± 0.04	

\* Only one mean measurement fell outside the selected range of clinical acceptability

TABLE 3

NUMBER OF RAW MEASUREMENTS OUTSIDE THE RANGE OF CLINICAL ACCEPTABILITY

Model type	Solid				Shell					
	0°	70°	90°	0°	70°	90°	0°	70°	90°	
Print angle										
Incisor Height*	1	0	0	0	0	0	0	0	0	0
Canine Height*	2	0	0	7	0	0	0	0	0	0
Premolar Height	0	0	0	0	0	0	0	0	0	0
Molar Height*	0	0	0	1	0	0	0	0	0	0
Incisor Width	0	0	0	0	0	0	0	0	0	0
Canine Width	0	0	0	0	0	0	0	0	0	0
Premolar Width	0	0	0	0	0	0	0	0	0	0
Molar Width	0	0	0	0	0	0	0	0	0	0
Intermolar Width*	1	0	0	0	0	0	1	1	2	2
Intercanine Width	0	0	0	0	0	0	0	0	0	0
Arch Depth	0	0	0	0	0	0	0	0	0	0
Total	4	0	0	8	0	0	1	1	2	2

## CHAPTER 4

### DISCUSSION

3D printing is continuing to be more utilized in orthodontic practice. Consequently, interest has arisen in determining whether the desktop 3D printers are able to produce adequately accurate models for use in orthodontic practice, specifically as it relates to clear aligner fabrication. Studies have investigated the accuracy of the models across different printers that utilized various additive manufacturing technology (Kim et al. 2018). Other studies have investigated the position of the object on the print platform (Sherman et al. 2020), print layer thickness (Loflin et al. 2019), print angulation (Short et al. 2018; Ko et al. 2021), and model body type (Kenning 2020; Rungrojwittayakul et al. 2020). These studies largely concluded that the common 3D printers produce models are clinically acceptable. However, each of these parameters was studied under different conditions and with different variables. The present study addressed print angle and model body type independently as well as how they interact with each other. It was also limited to models printed with a DLP printer.

Several studies have been conducted to research the effect of print angle on accuracy of 3D printed models. Studies by Short et al. and Ko et al. suggest that changing the angle of the print does have a statistical impact on the accuracy of the models. These studies were done with SLA and DLP printers, respectively. In the study by Short, 0°, 20°, and 90° models were compared. All three models showed measures within the range of clinical acceptability. Ko's study investigated differences at different layer thicknesses as well as four print angles of 0°, 30°, 60°, and 90°. Again, there were statistically significant differences, however, the average deviation from the master model for each print angle and



layer thickness were within the clinically relevant range of  $\pm 0.25$  mm. In summary, our study confirms previous findings that print angulation has an impact on accuracy, though not a clinically relevant one.

Other studies investigated the effect of model body type on model accuracy. Two independent studies showed that hollow models are clinically acceptable when the shell is at least 2 mm thick (Kenning 2020; Rungrojwittayakul et al. 2020). This thickness was used in our study to test whether a shell model could be printed at different angles and maintain clinical acceptable accuracy. Consistent with the other articles investigating model body type and accuracy, both the solid and the shell models demonstrated adequate accuracy. Beyond evaluating single factors, one previous study reported that print layer thickness and print angle have an impact on each other (Ko et al. 2021). However, the current study is the first to evaluate model type in combination with print angle, with no effect on clinical accuracy.

### **Clinical Implications**

While the goal of this study was to determine clinical acceptability of 3D printed orthodontic models, it was also important that the models were printed in a fashion optimized for the clinical workflow. This consideration has not been addressed in many of the other previous studies. Although print angle and model body type have the potential to increase efficiency and reduce time and material use, when not configured properly, variations in these factors can actually decrease efficiency and increase cost and waste. Consequently, this study aimed to investigate printing accuracy under circumstances that would be clinically useful.

In other studies, the models are printed at angulations that do not fit into an efficient workflow. For example, models printed at  $65^\circ$ , as seen in other studies (Kenning 2020),

require supports for the printed model. Though this angle allows for an increased number of models to be printed simultaneously (relative to models printed at  $0^\circ$ ), this configuration is less practical for a high-volume aligner fabrication workflow due to the extra time for removing the supports as well as the increased use of resin. Low angle print jobs, such as  $20^\circ$  as used by Short et al., do not allow for more models to be printed on the platform at a time (Short et al. 2018) Thus, a smaller angle print job adds the disadvantage having supports while not providing the advantage of printing more models at a time.

Shell models have the potential to substantially reduce the amount of resin used per model. Therefore, if printing as a shell is accurate, it would reduce cost because less resin is required for the print job. Studies regarding shell thickness have concluded that if the models are 2 mm thick, they are dimensionally accurate and withstand the heat of the thermoforming process (Kenning 2020; Rungrojwittayakul et al. 2020). Though these previous studies were effective at showing that models printed as a 2 mm shell are accurate, they both printed the experimental models in ways that would increase print time and pre/post processing. In one study, all models were printed at  $65^\circ$  and required several supports (Kenning 2020). Another study printed flat on the print platform ( $0^\circ$ ), which required vent holes to be built into the models, a variation that requires additional software and time prior to printing (Rungrojwittayakul et al. 2020) (fig. 11). This vent hole must also be filled with wax or putty when making the thermoformed aligners; otherwise, the thermoforming plastic will break as the plastic is forced through the vent. The shell models printed flat on the platform are also more prone to breakage when being removed from the platform.

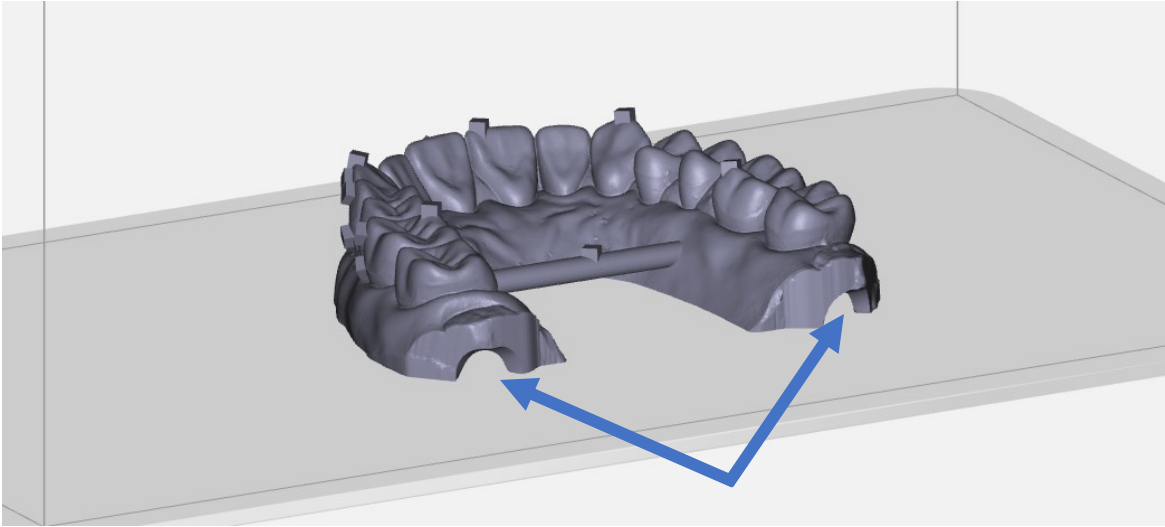


Figure 11. Vent holes required on 0° shell model.

All of these factors led to the decision to print at 0°, 70° and 90°, as none of these models require additional supports. The 0° shell model was used so it could be compared to the findings in a similar study (Rungrojwittayakul et al. 2020). However, this type of model would not be recommended in practice for the reasons mentioned above.

These considerations provide additional useful information to the clinician as practical application was considered in the experimental design. The finding that almost all mean values for all the models were clinically acceptable suggests that clinicians can utilize varying printing strategies as indicated by various clinical scenarios. For example, if a practitioner desired to print several models overnight and there is not a strict time restraint, then printing at 90° is advantageous, as more models can be fit onto the print platform. As shown in figure 12A, fifteen shell models can be printed at a time. This print job will take one hour, and forty minutes (not including twenty minutes of post processing) and each model uses nine mL of resin, which costs

about \$1.35 per model. The same fifteen-model print job can be done with solid models. This will take two hours and nine minutes, use about seventeen mL of resin per model and costs roughly \$2.50 per model. If a faster turnaround time is needed, then printing at 0° is preferred (fig. 12B). Only five models fit on the platform, but the print job only takes forty-three minutes (not including twenty minutes of post processing). Because a solid model is ideal for the 0° printed model, the amount of resin and dollar amount per model will be largely unchanged with changing print angulation (seventeen mL of resin and \$2.50 per model).

Overall, this study demonstrates the capabilities of a certain DLP printer. Specifically, orthodontic models can be accurately printed at varying angles and model body type. Furthermore, the angles and body type in this study are those that would be most useable in an in-house aligner workflow.

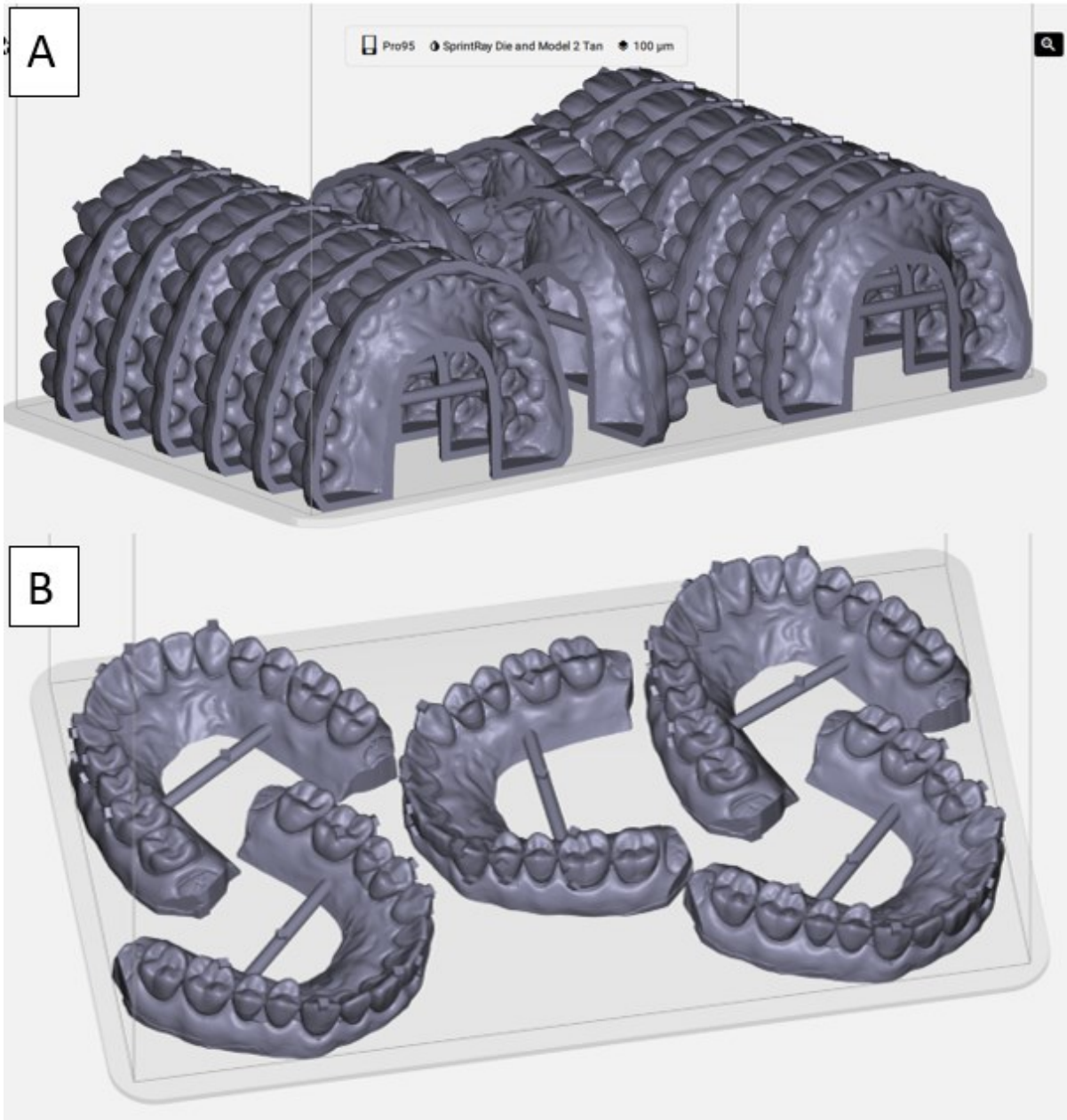


Figure 12. Digital models on the digital print platform. A. Fifteen 90° shell models on the digital print platform. B. Five 0° solid models on the digital print platform.

## Study Limitations

As with any study, there were some limitations. First, only one DLP printer was used to print the models. Thus, the results do not necessarily apply to all DLP printers, nor do they apply to SLA, polyjet, or FDM printers.

A second limitation is associated with the measuring technique. In this study, the experimental models were measured with a measuring microscope and the master model measured using computer software. This means that the measurements were all linear measurements to corresponding points. Therefore, a 3D comparison, between the experimental models and master model could not be made, as was done in other studies utilizing superimposition software (Kim et al. 2018; Short et al. 2018; Ko et al. 2021; Williams et al 2022). In the other studies, a model was scanned, then modified and printed, then scanned again. After this, the digital copy of the experimental model was superimposed over the master model. However, while those studies included 3D evaluations and heat mapping to better visualize the printing differences (fig.13) and employed faster methods of data acquisition, one advantage of the current study was that the need for a second scan, and the potential associated scanning-related errors, were eliminated. In other words, this study compared the digital master model directly to the printed experimental models (Scan -> Print -> Measure). Whereas other studies compared a digital master model to the STL-model generated from a scan of the experimental model, a step which could introduce error (Scan -> Print -> Scan -> Measure). Yet, the fact that the findings in this study were consistent with the findings in studies using superimposition software, suggests that either of the methods can be used in future studies.

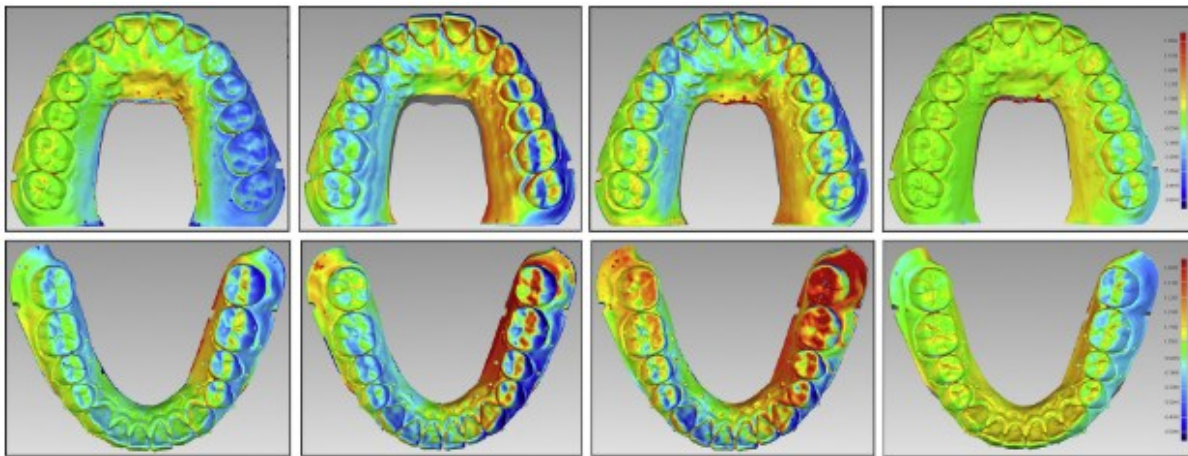


Figure 13. Example of heat mapping data. Colors correspond to degree of error. Acquired from research conducted by Kim et al. (2018)

An important consideration of this study and other similar studies is evaluating the results based on clinical significance. However, unfortunately, clinical acceptability has not been specifically defined in a document such as an International Standards Organization (ISO) specification as is done in the ISO specification for impression materials. Because of that, there are variations in the definition of acceptable clinical accuracy between studies ranging from 0.16 mm to 0.5 mm (Camardella et al. 2017a; Short et al. 2018). In the current study, any measurement differences greater than  $\pm 0.25$  mm for any single tooth measurement and  $\pm 0.5$  mm for cross arch measurements were considered clinically significant. These numbers relate to the amount of tooth movement per tray as well as the PDL width. It should also be noted that the parameters for accuracy in this study are specific to orthodontic purposes. The results should not be applied to other dental purposes such as restorative, as restorative applications require levels of accuracy of at least  $\pm 0.1$  mm (Osman et al. 2017; Rungrojwittayakul et al. 2020).

## **Future Investigations**

This study was designed to evaluate model accuracy and highlight aspects of 3D printing in orthodontics that maximize efficiency in the fabrication process. Future studies that focus on clinical efficiencies can build on aspects of the research done here. A very similar study could be done with models without the crossbar, which was introduced for better comparison to other studies comparing solid and shell models with a crossbar (Rungrojwittayakul et al. 2020). A future study could address the impact of a crossbar on model distortion to verify whether printing vertically can be done without the crossbar. This modification would help to further reduce time for model pre- and post-processing.

Print layer thickness is a variable that has previously been studied, with findings that 100-micron layer thickness is clinically accurate (Loflin et al. 2019). However, the printer that was used in the current study has been updated to allow a 170-micron layer thickness. This thicker layer would allow for even faster print times, which would also be beneficial from an efficiency standpoint. A study comparing accuracy of 170- vs 100-micron layer thickness could validate the use of the thicker layer (and faster print times) for orthodontic purposes.

Esthetics of the aligners themselves is another aspect of this process that could be studied. During this study, it was noted that the facial surface of the incisors has a different appearance based on the orientation of the printed model. The contour lines from each cured layer are visible on the model and are transferred to the thermoformed appliances. It would be worthwhile to know whether there is a patient preference or perception regarding these esthetic differences, as well as any functional differences. Along these same lines, investigating whether different print angles yield better esthetics/function/morphology



relative to the other print angulations may be of value, especially as printing at an angle has shown superior surface qualities in other facets of dentistry such as crown and bridge work (Osman et al. 2017).

## CHAPTER 5

### CONCLUSION

Under the conditions of this study, orthodontic models can be 3D printed at varying angles and model body types while maintaining clinically acceptable accuracy.

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## VITA

NAME: Bryndon James Belnap

DATE AND PLACE OF BIRTH: November 4, 1989; Pocatello, ID

### EDUCATION:

May 2008	Diploma	Pocatello High School, Pocatello, ID
May 2016	B.S. Biology- biomedical sciences	Idaho State University, Pocatello, ID
May 2020	D.D.S.	Creighton University School of Dentistry
December 2022 In Process	M.S. Oral and Craniofacial Sciences	University of Missouri-Kansas City School of Dentistry Kansas City, MO
December 2022 In Process	Orthodontics and Dentofacial Orthopedics	University of Missouri-Kansas City School of Dentistry Kansas City, MO

### PROFESSIONAL ORGANIZATIONS:

2016-Present	American Dental Association
2020-Present	American Association of Orthodontics

### HONORS:

2019	Alpha Sigma Nu Inductee
2020	Omicron Kappa Upsilon Inductee