The Effect of Build Angle on Compressive Strength of 3-D Printed Orthodontic Aligners

by

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Introduction: The current process of fabricating orthodontic aligners is by vacuum forming a sheet of plastic over a stone cast or printed model of the patient's dentition. As technology in dentistry advances, the capability to directly print an orthodontic aligner will be a reality. The aim of this study is to test the compression strength of directly 3D printed orthodontic aligners printed at various angles. **Methods:** A maxillary typodont was scanned using an intraoral scanner and the STL file was used to digitally create a 0.75 mm thick aligner. This aligner was printed at 0°, 30°, 60°, and 90° in relation to the build plate. Eight aligner were 3D printed at each angle being tested using Dental Long Term clear resin. After post processing, the supports were removed and the aligners were compression tested using an Intron 5566 universal testing machine. The failure point of each aligner was recorded. The hypothesis is that aligners printed at steeper angles will be weaker in compression. **Results:** Thirty-two aligners were compression tested. The mean failure points of each group of aligners was as follows: the 0° aligners failed at 847 N, the 30° aligners failed at 877 N, the 60° aligners failed at 717 N, and 90° aligners failed at 811 N. A Kruskal-Wallis test was used to analyze the data and found no statistically significant difference between the four groups (p=0.09). **Conclusions:** The build angle does not significantly affect the compression strength of 3D printed orthodontic aligners. Orthodontic providers should use this

data along with other studies to determine how best to orient their aligners to maximize efficiency during direct 3D printing.

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Preface

I would like to thank Dr. John Burnheimer for leading the research committee and for his encouragement and support throughout the process. I would also like to extend gratitude toward Dr. Suvendra Vijayan for printing the aligners for this study. Thank you to Dr. Nilesh Shah for his guidance regarding data collection and his statistical analysis thereafter. And thank you to Dr. Alejandro Almarza and John Li for teaching me how to use the Instron.

1.0 Introduction and Statement of the Problem

In the last decade, there has been a sweeping transition within orthodontic practices towards using clear aligner therapy (CAT) in place of traditional fixed appliances. The increase in adults seeking orthodontic care has driven the need to create an inconspicuous treatment option that fits their lifestyle and desire for discretion during treatment. In addition to being one of least visible and most esthetic orthodontic treatment options, CAT also provides patients certain freedoms that traditional braces may not. Aligner patients can remove their appliances before meals and eat foods usually not permitted during braces. Similarly, tooth brushing and flossing is much easier with aligner treatment as there are no brackets and wires to navigate around. As a result, patients using CAT may present with healthier teeth and gingiva. Finally, there are fewer emergency visits to the orthodontist as patients do not have a sudden poking wire or broken bracket that needs attention.

In the years following their inception, the clinical use of clear aligners was limited to mild malocclusion and were not indicated to treat a wide variety of orthodontic needs. With the advancement in attachment design, improvements in digital treatment planning, and a better understanding of how to successfully move teeth with plastic, increasingly complex cases have been treated successfully with CAT. Not only have clear aligners as a product improved, but the patient workflow has upgraded from traditional impressions and stone models to digital scans and virtual models.

Historically, the workflow to start an aligner case included taking polyvinyl siloxane (PVS) impressions and a bite registration of a patient and mailing them to one of a few companies that fabricated aligners. That practice has mostly gone by the wayside in favor of intraoral scanning. The use of intraoral scanners in orthodontics has revolutionized the field and allowed for a digital workflow to be used for diagnostic models, treatment planning, and appliance fabrication. In addition to creating a better experience for the patient, making digital models also frees up office space by eliminating the need to store stone models of every patient.

After the pivot to intraoral scanning came the possibility to convert the digital models into standard tessellation language (STL) files and 3-D print them using resin. 3-D printed models have properties superior to stone models as they do not chip or break as readily, and they can be reprinted if they are lost or broken without needing to reappoint the patient. With the decrease in size and cost of 3-D printers in recent years, in-office 3-D printing equipment has become commonplace in orthodontic practices. This has allowed the orthodontist to print patient models without outsourcing to a lab. Certain dental appliances, like night guards, can also be directly printed.

Presently, the only way to fabricate an aligner is by vacuum forming a thermoplastic sheet over a resin model or stone cast. As technology continues to evolve, the next step would be to have the capability to directly print the aligners themselves. Eliminating the need to have a printed model or stone cast is not only more efficient, but it cuts out a large expense as it saves resin, eliminates the need to buy thermoplastic sheets, and is more environmentally conscious as printed models are no longer needed and excess plastic from thermoformed sheets is not being discarded. Another factor that bolsters efficiency is printing as many aligners as possible in one session, accommodated best by positioning aligners at 90° on the build platform. What is not known is if the angulation during printing effects the integrity of the material.

Using currently available resin for 3-D printed occlusal splint fabrication, this study will compare the compression strength of 3-D printed aligners to identify if an increasingly steep build orientation influences their compressive strength.

2.0 Specific Aims

1. To compare the compressive strength of aligners printed at 0°, 30°, 60°, and 90°.
2. To determine if the findings of this study can make a more efficient the workflow of 3-D aligner printing.
3. To add to the limited research available on direct 3-D printed orthodontic aligners.

3.0 Background and Literature Review

3.1 Esthetics with Aligners

It is estimated that adults make up twenty five percent of orthodontic patients today (Orthodontists). The advancements in CAT likely have much to do with the rise in adults seeking orthodontic treatment. When asked to evaluate the attractiveness of smiling images of adults in various orthodontic appliances, 199 adult participants rated clear aligners and lingual brackets as most attractive, and color-ligated metal brackets as most unattractive. These participants preferred CAT for their own treatment, and indicated they would be willing to pay more to have aligners over braces (Azaripour et al., 2015). Didier et al. sought to discover if adults in orthodontic treatment were perceived more negatively by employers during job interviews than those without orthodontic appliances. Photo albums of one male and one female model were created with 7 photographs of each model: one photo without appliances, and 6 photos with different types of orthodontic appliances in place. These albums were given to 236 male and female evaluators in charge of hiring following job interviews. All other qualifications being equal, evaluators showed preference for applicants with clear aligners, followed by those without any appliances. Third preferred were those in ceramic brackets, followed by metal brackets with silver elastic ligatures. Least desirable were the applicants in metal brackets and blue colored elastic ligatures. This study showed that evaluators for employment have biases against adults in orthodontic treatment. Adults wearing more esthetic appliances showed a higher likelihood of being hired than those in fixed braces (Didier et al., 2019).

3.2 Oral Hygiene with Aligners

When it comes to oral hygiene during orthodontic care with CAT, most studies have found that patients treated with aligners present with superior oral hygiene compared to those with traditional braces. Buschang et al showed a 26% incidence of developing white spot lesions (WSL) during treatment with conventional braces, while only 1.2% of clear aligner patients finished treatment with WSL (Buschang, Chastain, Keylor, Crosby, & Julien, 2019). A meta-analysis by Wu et al compared the periodontal health of patients treated with fixed appliances and CAT. They found that patients using aligners had better plaque scores and gingival indices, and lower probing depths than patients in fixed appliances (Wu, Cao, & Cong, 2020). Compliance with proper hygiene practices was found to be higher among teenagers in treatment with CAT. Abbate et al found that Italian teenagers aged 10-18 treated with Invisalign™ showed greater compliance with hygiene instructions, and consequently had less plaque accumulation and gingival inflammation than their peers treated with fixed appliances (Abbate et al., 2015). Conversely, a randomized clinical trial by Chhibber et al compared the plaque scores, gingival indices, and periodontal indices of patients treated by CAT, self-ligating brackets, and conventional brackets requiring elastic ligatures. They found no significant differences in the quality of oral hygiene among the three groups after 18 months of orthodontic treatment (Chhibber, Agarwal, Yadav, Kuo, & Upadhyay, 2018).

3.3 Intraoral Scanning

Orthodontics has become increasingly digitized, leaving behind traditional procedures like impression taking in favor of digitized ones like intraoral scanning. While there is an upfront cost associated with acquiring scanning equipment as well as a learning curve for performing a scan, there are considerably more advantages. When surveying the pediatric patient population, it has been shown that both the clinician and the patient found intraoral scanning more comfortable and preferred it to alginate impression making (Yilmaz & Aydin, 2019). Similarly, orthodontic patients who experienced both alginate impressions and an intraoral scan were asked to complete a questionnaire measuring their comfort, stress, and preference of procedure. The data showed these patients were no more uncomfortable or stressed with one procedure over another, but they preferred scanning over impression making (Mangano, Beretta, Luongo, Mangano, & Mangano, 2018). While there is no statistically significant difference between the speed of creating a digital or an alginate impression (Mangano et al., 2018; Yilmaz & Aydin, 2019), impressions made of polyvinyl siloxane are more sensitive to moisture and have significantly longer setting times than alginate, making them a lengthier procedure than intraoral scanning.

The accuracy of an intraoral scanner is determined by "trueness" and "precision". Trueness can be defined as how similar a measurement is to an already known value. For instance, if the width of an object has been established to be 10 mm, how close to 10 mm is the scanned object when measured digitally. Precision on the other hand refers to the degree of reproducibility of the scanner when taking multiple scans and measurements of an object (Nulty, 2021). From the previously given example, does the object measure 10 mm dependably or is the measurement inconsistent.

In terms of the accuracy of scanning, a 2016 systematic review was conducted to determine if intraoral scanners produced reliable and valid inter-arch and intra-arch measurements when compared to measurements taken on stone models via impressions. The electronic databases used were PubMed, MEDLINE, Bireme, Scopus, Web of Science, Google Scholar, and Open Grey. Only four articles met the inclusion criteria and were used. The systematic review concluded that intraoral scanning is a reliable and valid means to assess inter- and intra-arch measurements when compared to conventional impressions and stone models (Aragón, Pontes, Bichara, Flores-Mir, & Normando, 2016).

Another systematic review was conducted in 2021which investigated the efficiency and accuracy of intraoral scanners when used in orthodontics. Literature searches were performed on MedLine (PubMed), Scopus, Web of Science, and Embase. They distilled the search to 16 articles that met their inclusion criteria of study design (randomized control, cohort, or case-control), publication in the previous five years, and written in English. All authors concluded that the accuracy of intraoral scanners is enough to replaced traditional stone models as the tissue mapping is equal or superior to the traditional impression technique. They also noted that scanning takes more chairside time than impressions but is more enjoyable for patients and providers alike. It was concluded that scanners of the same generation from different manufacturers have indistinguishable accuracy. The authors concluded that unless a new generation of intraoral scanners becomes available, further studies on scanner accuracy are redundant as it has been consistently proven that they produce an accurate intraoral record (**Error! Hyperlink reference not valid.**).

3.4 Dentistry and 3-D Printing

In concert with intraoral scanning is the capability to print any scanned item to create a physical representation of it. 3-D printing was once reserved for wealthy, high-tech companies as it was a process that required large and expensive equipment. As technology evolved, 3-D printers became less expensive and smaller in size, allowing them to be used in offices ranging from dentistry, medicine, as well as personal home use. In the dental field, intraoral scans are exported as STL files which are read by the 3-D printer. STL format represents a 3-dimensional surface in triangular facets. It is sometimes referred to as “Standard Triangle Language” or “Standard Tessellation Language” (Congress). Using a computer-aided-design (CAD) model taken from a scan, 3-D printing is an additive manufacturing process that can create a physical object by systematically adding layer after layer of resin until the part is made. In addition to optical scanning, the rise in popularity of cone beam computed tomography (CBCT) in dental offices creates another avenue for capturing 3-dimensional information that can be printed.

3.5 Styles of 3D Printers

There are several different techniques of 3-D printing which can be broken down into vat polymerization, material jetting, binder jetting, material extrusion, powder bed fusion, sheet lamination, and direct energy deposition. Each type can be further subdivide and will be described below (PRINTING.COM)

1. Vat polymerization uses a tank of light cured resin that employs a ultraviolet (UV) light or laser to selectively cure the resin to create an object. This is the most commonly used style of 3D printer used in dentistry. There are three subtypes of vat polymerization.
    a. Stereolithography (SLA) uses a UV laser that draws the shape of the object and cures the surface of the photopolymer resin onto a build platform. SLA printers most commonly work upside down, with the laser pointing up to the build platform which starts low in the vat and gradually elevates as each layer is cured.
    b. Digital light processing (DLP) is like SLA but instead of a laser it uses a UV light. It does not trace an outline of the object but rather uses a projector screen that projects an entire cross section, or layer, at a time that is cured by the light. This makes DLP faster than SLA.
    c. Continuous liquid interface production (CLIP) is the fastest of the resin polymerization printers. It continuously grows an object from the vat of resin using UV light to cure the resin where wanted, and oxygen to inhibit it where curing is unwanted.

2. Material jetting employs a nozzle which applies droplets of a material onto a build platform where it is cured by a UV light.

3. Binder jetting uses an inkjet print head which moves through a bed of powder and selectively deposits a liquid binding agent in the shape of the object to be printed. The completed section is then powdered and the process is repeated

4. Material extrusion is explained as follows.
    a. Fused deposition modeling (FDM) uses a spool of plastic that is fed through a nozzle. The tip of the nozzle heats up the plastic until it is malleable and extrudes it into a given shape. The nozzle moves around under the control of a predetermined digital design to lay down the warmed-up plastic until the object is formed.
    b. Fused filament fabrication (FFF) is the un-trademarked name for FDM. The printing process is the identical.

5. Powder bed fusion has several subtypes.
    a. Selective laser sintering (SLS) involves warming up powders of glass, plastic, ceramic, nylon to just below their melting point. Then, a pulsed laser selectively heats up the material to beyond its melting point so the particles melt and fuse in the shape of the object of interest. The powder bed is then lowered to re-powder the surface, and the process repeats.
    b. Multi jet fusion (MJF) works by using an arm which deposits a layer of powder onto a bed. Then a subsequent arm sweeps over the powder and selectively deposits binder liquid onto the powder. The powder and binder react to form a solid after a burst of thermal energy is introduced.
    c. Direct metal laser sintering (DMLS) is the same process as SLS but specifically with metal particles.
6. Sheet lamination binds together sheets of metal, paper, or plastic using an external force to push them together. In addition to force, metal sheets are bound using an ultrasonic welder

and paper sheets use glue. The sheets are then shaped by either a miller for metal, or blades for paper.

7. Direct energy deposition uses a nozzle which emits a collimated laser, electron beam, or other energy source to melt wire or metal powder that is put in its path and create a solid object after it cools.

3.6 Accuracy of 3D-Printing in Orthodontics

Despite all the benefits of digital models, there remains a time and place for physical models. Presently they are still needed to fabricate appliances like retainers, clear aligners, and functional appliances. Additionally, some orthodontists prefer to have a physical model to use as a teaching tool or when preparing cases for orthognathic surgery. Intraoral scans can be converted into physical models via 3D-printing. The question remains- how accurate is 3D printing with respect to orthodontic models?

Brown et al. compared the accuracy of stone models to those 3D-printed using a DLP printer and a polyjet printer. They took alginate impressions as well as intraoral scans on 30 retention patients. They made stone models from the alginate impressions and made digital models from their scans. The digital models were 3D-printed using a DLP as well as a polyjet printer. They measured first molar to first molar and compared mesiodistal crown widths, crown heights, intercanine width, intermolar width, and arch depth. Their results showed high agreement in measurements from stone, and both 3D printers. There was a statistically significant discrepancy between the stone and DLP printer measurements for crown height, with the DLP printed teeth measuring 0.29 mm smaller. The authors concluded that stone models can be replaced by both DLP and polyjet printers as they both produce clinically acceptable models. While there was a discrepancy in crown height with DLP printers, they stated it was within a clinically acceptable range (Brown, Currier, Kadioglu, & Kierl, 2018).

Ellakany et al. published an article comparing the accuracy of conventional stone casts to 3D printed ones. They scanned typodonts and 3D-printed the STL file of the maxillary and mandibular models using an SLA printer. They also made polyether impressions on the same typodont and made the models out of Type IV stone. Like the study by Brown et al., they measured crown width, crown height, intercanine width, and intermolar width. They concluded that while SLA printed models had more errors than stone models, they were within a clinically acceptable range. They stated that models printed from an SLA printer had similar accuracy to stone models and can replace them (Ellakany, Al-Harbi, El Tantawi, & Mohsen, 2022).
Dong et al. studied the accuracy of different tooth surfaces on 3D-printed dental models. In their study, they used an intraoral scanner to capture digital models of 30 patients. The digital models were converted to physical models using a DLP printer. They scanned the 3D-printed models and compared them to the digital models by superimposing the images and using color mapping to highlight the differences. They concluded that there were more deviations in the posterior teeth than in the anterior, and emphasized that pits and fissures of posterior teeth showed the greatest discrepancies. They recommended taking this into consideration when determining if 3D-printed models are appropriate to use for a given appliance or purpose (Dong et al., 2020).

Zhang et al. performed a study to compare dental models printed from DLP and SLA printers with a focus on the effect of layer thickness on accuracy. They randomly selected a digital dental model from their database to use for the study. The model was printed on a Form 2 (Formlabs, Somerville, MA, USA) SLA printer at 25, 50, and 100 μm layer thickness. The same model was also printed on three DLP printers. An EvoDent (UnionTec, Shanghai, China) DLP printer was used and the models were printed at 50 and 100 μm layer thickness. Models printed using EncaDent (Encashape, WuXi, China) DLP printer were printed at 20, 30, 50, 100 μm layer thickness. And finally, a Vida HD (EnvisionTec, Dearborn, MI, USA) DLP printer was used and models were printed at 50 and 100 μm layer thickness. They converted all printed models to digital models and compared them to the original digital model from the database. They concluded that all printers had the highest accuracy at 50 μm layer thickness. When the thickness was adjusted to 100 μm, the printing speed and accuracy of DLP printers were both superior to the SLA printer. The EvoDent printer at 50 μm thickness had the highest overall accuracy, and the Form 2 printer at 100 μm thickness had the lowest print accuracy (Zhang, Li, Chu, & Shen, 2019).

Naeem et al. studied the precision and trueness of 3D-printed orthodontic retainers. They used four different styles of printers: SLA, DLP, continuous DLP, and polyjet photopolymer. They concluded that SLA and polyjet photopolymer printers were the most accurate and DLP and continuous DLP were the most precise. They emphasize that future studies are needed to know if how these printers influence fit of the appliances (Naeem et al., 2022).

3.7 Object Orientation During 3-D Printing

In the SLA print style, the operator can choose the angle at which the object of interest is printed. This angle is in reference to the build platform, and steepening or flattening it presents certain benefits and drawbacks. Printing an object vertically, at 90°, takes up the least amount of space on the build platform, and allows for printing of multiple objects at one time. A downside to printing in a vertical orientation is that it creates a taller object that requires more layers of resin to be cured which can take more time and may increase the chance of print failure (Favero et al., 2017). Conversely, printing an object flat on the build platform has the biggest footprint on the platform which diminishes the ability to print multiple objects. The upside is that this orientation prints quickly as the object is short and does not extend far from the platform. Some studies show that print orientation can affect the material properties of the object being printed. Osman et al showed that different build angles produce dental restorations of differing dimensional accuracy (Osman, Alharbi, & Wismeijer, 2017). Similarly, Rubayo et al found that surgical templates printed at 0° and 45° were more accurate than those printed at 90° (Rubayo, Phasuk, Vickery, Morton, & Lin, 2020).

Ko et al studied the effect of build angle and layer height on accuracy of 3D-printed models. They scanned a maxillary cast and printed 132 models on a DLP 3D printer at 0°, 30°, 60°, 90° and 20, 50, and 100 μm thickness. The printed models were scanned and compared to the original digital scan using a 3D best fit algorithm. They found that the models printed at 0° angulation and 20 μm thickness were the least accurate. They concluded that there was a tendency for 30° or 60° build angles with smaller layer height of 20 and 50 μm to print the most accurate models, but all deviations among the different angulations and thicknesses were within clinically acceptable ranges (Ko et al., 2021).

3.8 Thermoformed Aligners

The current workflow to make clear aligners starts with intraoral scanning a patient and then using digital software to move the teeth to the desired position. A physical model is then made via 3D printing. A maxillary and mandibular model is needed for every aligner in the series of treatment. Then the aligner is fabricated by heating up and vacuum forming a thermoform sheet of plastic over each of the models and then trimming them for patient comfort. This process is not only very tedious and time consuming but also creates a lot of unnecessary waste.

Several different materials are used to make thermoformed plastics amenable to orthodontic aligner fabrication. The most common is polyethylene terephthalate glycol, although other materials such as polyurethane, polyethylene terephthalate, polyvinyl chloride, and copolyester can also be used (Ercoli, Tepedino, Parziale, & Luzi, 2014; Pithon, 2012). A benefit to these materials is that they are relatively inexpensive and simple to use. A thermoformed aligner does not require exacting software or complicated equipment. Overall, thermoplastic materials have been a predictable and reliable material to use for orthodontic aligners. It is worth noting that thermoformed aligners present with some unique property behaviors of which a user should be aware. Ryu et al evaluated the physical and mechanical properties of thermoformed materials used for aligners. Their study found that after thermoforming, the transparency of Duran and Essix A+ materials decreased while the water absorption and water solubility of Duran, Essix ACE, and Essix A+ increased (Ryu, Kwon, Jiang, Cha, & Kim, 2018). Although not statistically significant, of notable mention is the study by Bucci et al. which found that the thickness of the aligner decreases slightly after thermoforming (Bucci et al., 2019).

When evaluating the properties of the various thermoformed materials after exposure to the oral environment, it has been shown they do not preserve their shape or original composition. After a two-week immersion in a simulated oral environment, thermoformed plastics exhibited decreased thickness compared to pre-thermoforming and a change in molecular structure leading to an increase in water absorption, a decrease in tensile yield strength, and either a significant increase or decrease in elastic modulus, depending on the brand (Ryokawa, Miyazaki, Fujishima, Miyazaki, & Maki, 2006). Increased water absorption is particularly undesirable as it may alter the fit of an appliance. A comparable study found that intraoral aging significantly affected the mechanical properties of Invisalign™ aligners. After retrieving used Invisalign™ aligners from patients and comparing them to unused controls, Bradley et al. showed that the used aligners were more brittle than the controls and had degradation of their mechanical properties which clinically correlated to a decaying orthodontic force over time in the mouth (Gerard Bradley, Teske, Eliades, Zinelis, & Eliades, 2015). Futhermore, Invisalign™ aligners worn for 14 days showed micro cracks, areas of delamination, and reduced transparency (Gracco et al., 2009).

Jindal et al studied the mechanical and geometric properties of 3-D printed clear aligners and compared them to thermoformed aligners. They found that 3-D printed and properly cured aligners have better geometric accuracy, load resistance, stiffness, and deform less readily than thermoformed aligners. They also found that 3D printed aligners that were uncured had a compression strength more similar to thermoformed aligners than properly cured 3D printed aligners. This could be useful if a more pliable aligner is needed for a specific clinical scenariolike the beginning stages of treatment, or in the treatment of a patient with a strong bruxism habit (Jindal, Juneja, Siena, Bajaj, & Breedon, 2019).

4.0 Purpose of the Present Investigation

What the literature is lacking is a comparison of the compression strength of printed aligners at increasingly steeper build angulations. The hypothesis being tested in this study is that orthodontic aligners printed flat (0°) will show a higher compressive strength than those aligners printed at increasingly greater angles.

Orthodontic providers should be cognizant of the compression strength of their aligners because they ask their patients to wear the appliance close to 22 hours a day, including during sleeping. It has been shown that patients with nocturnal bruxism can produce a bite force close to 800 N (Nishigawa, Bando, & Nakano, 2001). Are 3D printed aligners compatible for use in patients with these parafunctional habits?

5.0 Materials and Methods

5.1 Sample

A series of clear orthodontic aligners will be 3D printed using a Form 2 SLA printer (Formlabs, Somerville, MA, USA) with Dental LT Clear V2 resin (Formlabs, Somerville, MA, USA). This is the second-generation biocompatible resin used for making splints, occlusal guards, and long term orthodontic appliances (FormLabs). Eight aligners will be printed at each of the following angles: 0°, 30°, 60°, 90° for a total of thirty-two aligners.

5.2 Data Acquisition

Using a Trios 3 Scanner (3Shape™, Copenhagen, Denmark), the maxillary arch of a typodont used for patient education on clear aligners was scanned. Attachments were present on the first and second premolars to simulate scanning a patient undergoing aligner therapy. A 0.75mm thick aligner was digitally designed to fit over the scanned maxillary dentition using Ortho Studio V5 (Maestro3D, Pisa, Italy) (Figure 1). The STL file of the maxillary aligner was uploaded into Meshmixer (Autodesk Inc; San Rafael, CA, USA) and prepared for 3D printing. The aligners were fabricated from Dental Long Term clear resin. A Form 2 SLA printer was used for aligner printing. The aligner was printed at 100 μm layer thickness and at four different angles in relation to the build plate: 0°, 30°, 60°, and 90° (Figure 2). Ten copies of the aligner were printed at each angle of interest for a total of forty identical aligners, differing only in the angle they were printed. Printing ten aligners per group allowed for two extra aligners in each group in case of a misprint or breakage during handling. Following the print, the aligners were washed in 99% isopropyl alcohol and cured at 60°C for sixty minutes in a ProCure unit (SprintRay). After the completion of curing, each aligner's print angle was written on it with a permanent marker to avoid mischaracterization following removal of supports. The aligners were then prepared for compression testing by removing the structural supports using a metal disc on a straight nose slow speed hand piece (Figure 3). Once all the aligners were freed from their supports, they were brought to an Instron 5566 Universal Testing Machine (UTM) (Illinois Tool Works Inc., Norwood, MA, USA) to measure compression strength.

Because the aligners slide around easily on the metal platform of the UTM, an L-shaped framework was built from tongue depressors and taped to the platform (Figure 4). This allowed for standardization of aligner placement on the platform, centered under the compression platen, and decreased chance of variability in results due to inconsistent positioning. The right side of the aligner was loosely taped down to the platform to prevent sliding but allow displacement during testing. A circumferential shield was placed around the platform and fastened in place (Figure 5). This prevented fragments of the aligner from dispersing throughout the room upon fracture. A 2kN load cell was loaded into the UTM. A load cell is a critical part of the machine which converts the delivered force into an electrical signal (Instron) and corresponds to the maximum force the system can take. In preparation for compression, the compression platen was manually lowered until it was within a few millimeters of touching the aligner. Compression testing was then ready to begin.

Bluehill Universal Materials Testing Software (Illinois Tool Works Inc., Norwood, MA, USA) was used to record the behavior of each aligner as it was gradually compressed. The compression platen was programmed to lower at a rate of 5 mm per minute. The Bluehill software produced a graph of compression force over time as the compression testing was in progress. The testing was stopped manually when the failure point was achieved. In addition to an audible crack in the aligner, failure point was evident by a sudden and sharp decrease in force on the graph (Figures 6 and 7). This process was repeated for all 32 aligners that were tested.

Data points from Bluehill software were transferred to Excell (Microsoft, Seattle, WA, USA) for organization and preparation for data analysis.

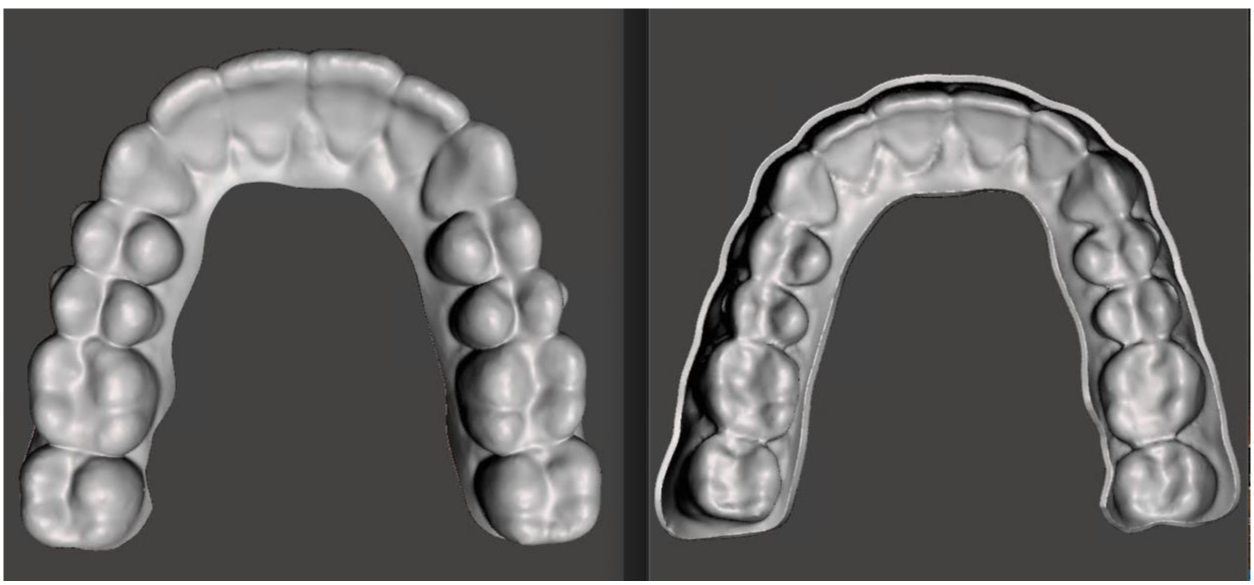

Figure 1

Images of the digital aligner from the occlusal and intaglio surfaces.

Figure 2

The printed aligners with supports

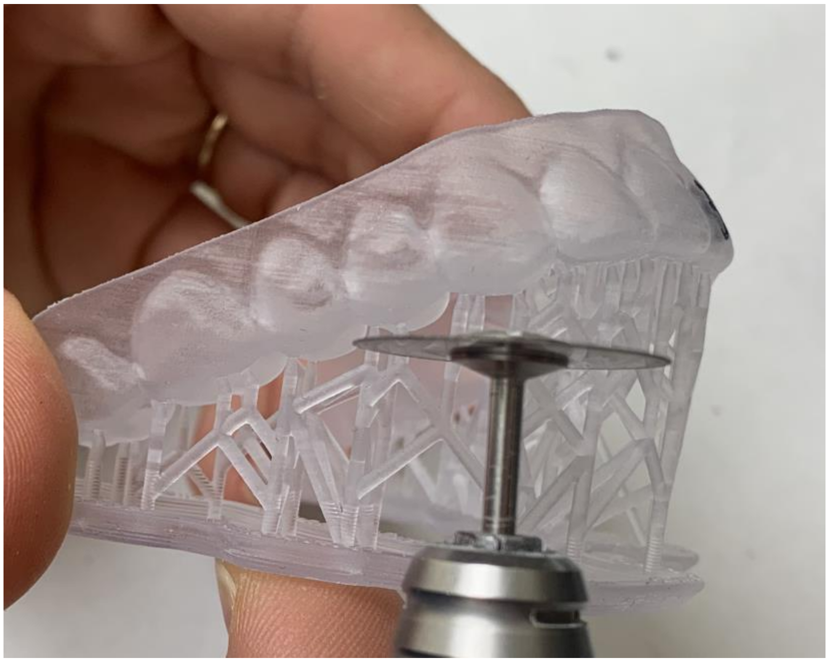

Figure 3

Removal of the supports using a metal disc on a straight nose slow speed

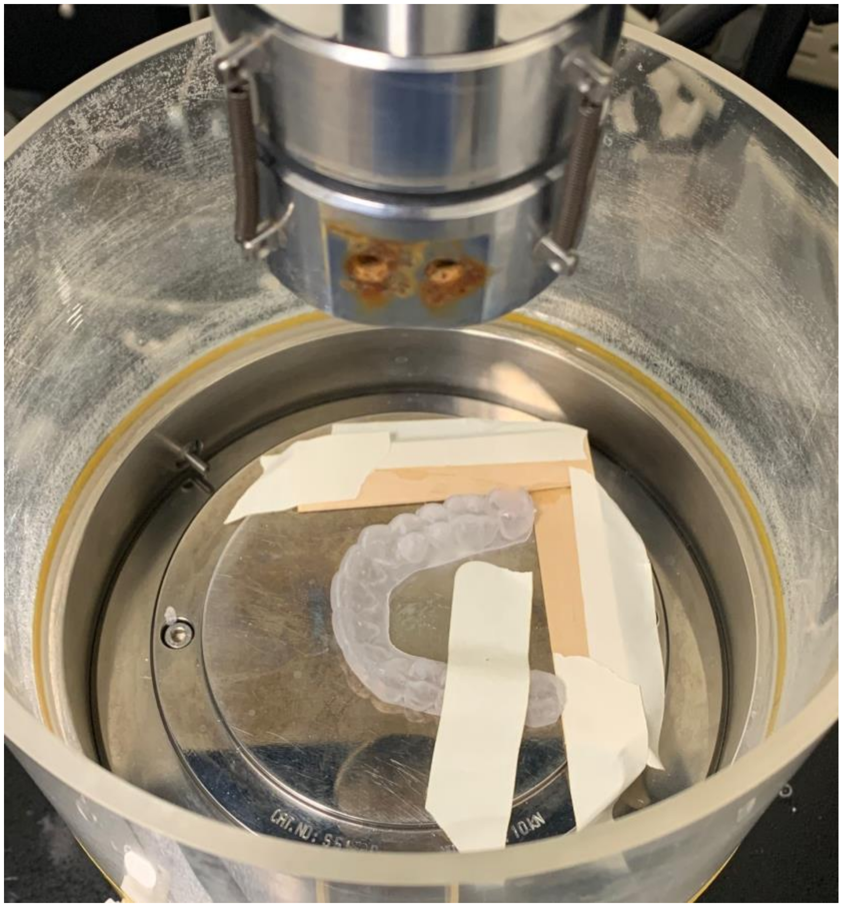

Figure 4

The L-shaped framework used to standardize placement of aligners.

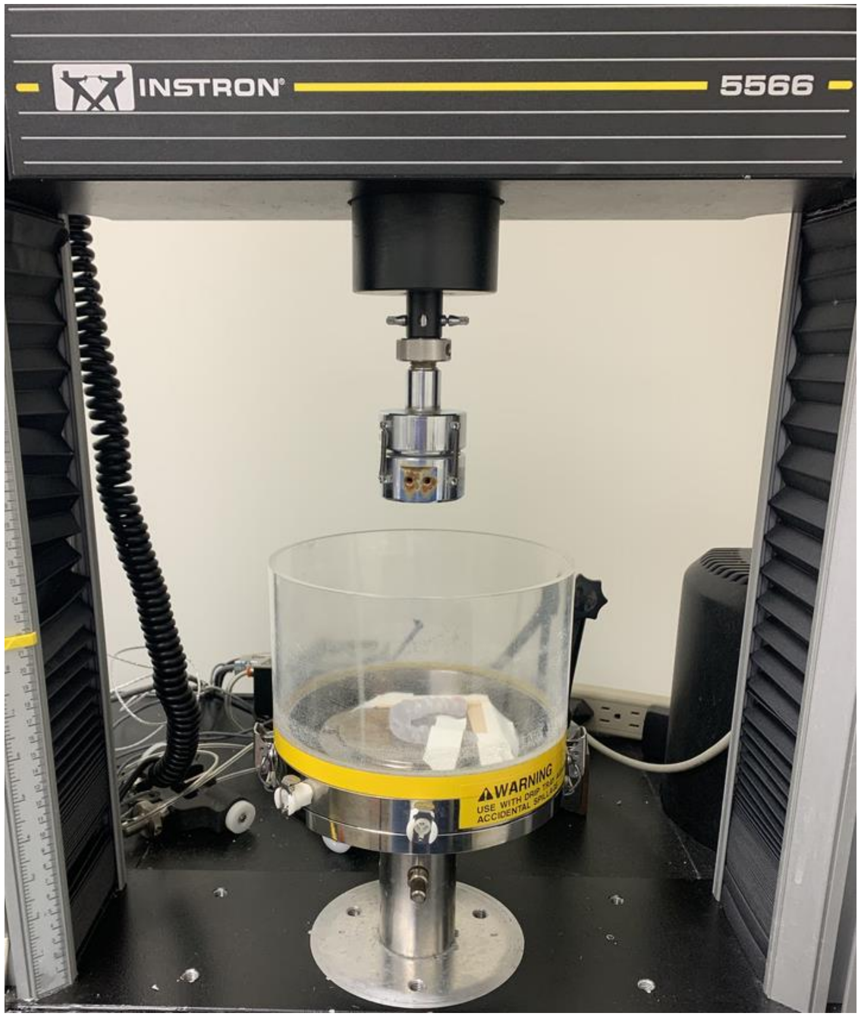

Figure 5

An aligner positioned for compression. The compression platen above it ready to be lowered.

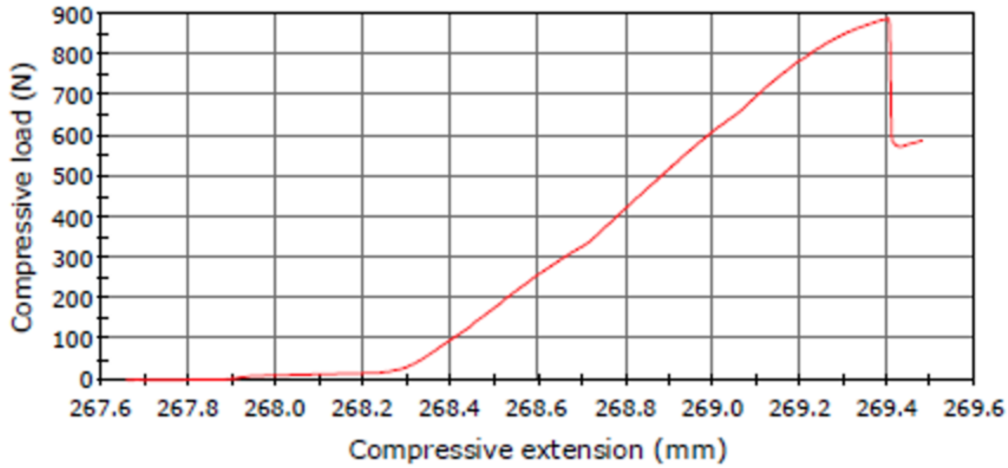

Figure 6

A force/displacement curve showing the compressive load over millimeters of displacement and failure point

Figure 7

A cracked aligner after compression

5.3 Statistical Methods

With an alpha = .05, a power of = 0.80, and an effect size of 50 N, the projected sample size needed with this effect size is approximately n = 5. Thus, our proposed sample size of eight aligners per group will be more than adequate to satisfy the main objective of this study.

A one-way ANOVA test was initially used to analyze the data (p=0.06). To verify that the assumption of equal variances was met, a Bartlett's test was run. The data did not pass Bartlett's test (p=0.020), therefore the data cannot be assumed to have means with equal variances. Therefore, a non-parametric test was needed.

A Kruskal-Wallis test was used to determine if there was significant differences between all the medians for maximum force tolerated before failure. All statistical analysis was done using Stata 16.1 software.

6.0

Forty aligners were printed in total. Two aligners experienced misprints and were discarded. Two other aligners cracked during support removal and were not used. Thirty-two sound aligners were compression tested, eight per group. All the aligners demonstrated a similar failure pattern of cracking on the left side (Figure 7).

The failure points of the aligners printed at 0 degrees had the largest range of any group. Failure was reached between 620-1088 N of force with an average failure point at 847.25 N. The failure point of the aligners printed at 30 degrees ranged from 733-1079 N with an average failure point of 877 N. The aligners printed at 60 degrees had the narrowest range of failure points, tolerating peak compression between 622- 769 N with an average failure point at 717.63 N. And lastly, the aligners printed at 90 degrees could withstand maximum pressure between 660- 935 N with an average of failure point of 811.88 N. These results are summarized in Figures 8 and 9.

The Kruskal-Wallis test in Table 1 showed that there were no significant differences between the failure points of any of the groups (p=0.091).

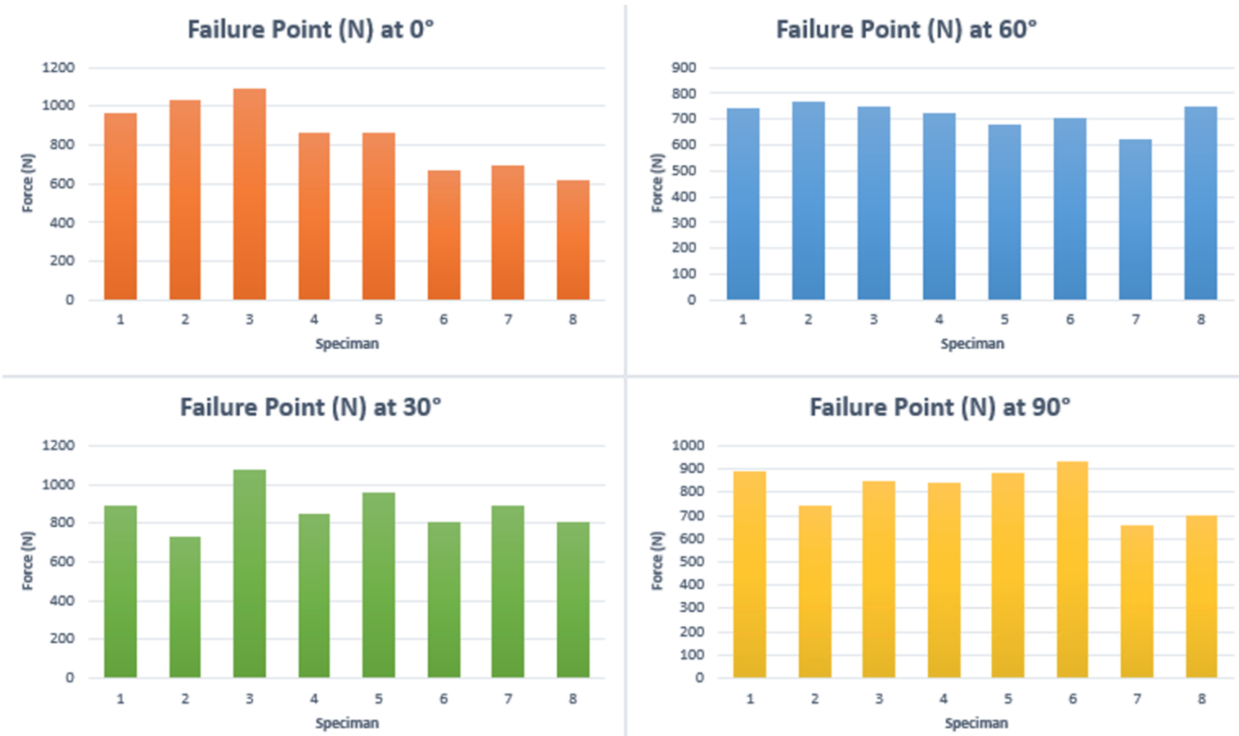

Figure 8

The failure points of each of the 32 aligners tested.

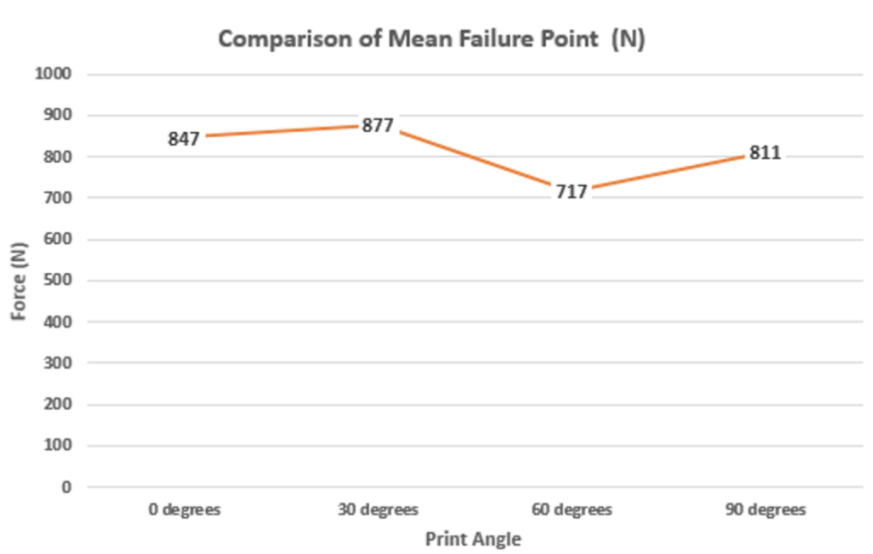

Figure 9

The mean compression strength of each group of aligners.

Table 1

Kruskal Wallis Test Results

Degrees	Observations	Mean Failure point (N)	Rank Sum
0	8	847	144
30	8	877	172
60	8	717	79
90	8	811	133

$p=0.0909$

7.0 Discussion

The aim of this study was to evaluate if the print orientation affects the compression strength of directly printed orthodontic aligners. The hypothesis was that the lower the build angle, the higher the compression strength of the aligner. The data showed that not to be the case. The aligners with the flattest build angle of 0° had a mean failure point at 847 N. The aligners printed at 30° withstood greater compression than the 0° group, reaching failure at a mean of 877 N. The failure point dropped to 717 N with aligners printed at 60° and then increased to 811 N for aligners at 90°. The data showed no consistent pattern between the groups, and there was no significant difference in compression strength between aligners printed at 0°, 30°, 60°, and 90°. This indicates that our hypothesis that aligners would be increasingly weaker at greater print angles is rejected and the null hypothesis accepted.

It is worth noting that the aligners printed flat on the build plate (0°) had the widest dispersion of data. They exhibited the lowest failure point at 620 N as well as the highest at 1088 N. While we initially thought that these aligners would be the strongest, the results showed that they were the most unpredictable. The narrowest dispersion of data was seen by the aligners at 60° which showed failure points between 622-769 N. This data dispersion is similar to previous studies that showed aligners printed at 45° had a smaller standard deviation than those printed at 0° and 90° (McCarty, Chen, English, & Kasper, 2020). These finding differ from that of Boyer et al who found that aligners printed flat, at 0° or 180°, as well at perpendicularly at 90° had the smallest standard deviation with respect to dimensional accuracy (Boyer, Kasper, English, & Jacob, 2021).

Additionally, the aligners printed at 90° had supports that were the most difficult to remove because they ran parallel to aligner and embedded themselves in the intaglio surface. They required more care during support removal as to not violate the aligner itself. Despite this constraint, the 90° aligners did not perform significantly inferior to the other groups which indicates that the supports were removed consistently with those on other aligners without the introduction of error.

Past studies that have evaluated the print angle of orthodontic aligners have shown differing results. McCarty et al studied 3D printed aligners at 0°, 45°, and 90° to the build platform to discover if the print angle influences the dimensional accuracy of the aligner. In addition to print angle, they also cured the aligners for varying amounts of time. They concluded that neither the angle nor the post print cure time significantly affected the dimensional accuracy of the aligners (McCarty et al., 2020). Conversely, Rubayo et al concluded that print orientation does affect the accuracy of 3D printed surgical splints, with those printed at 0° and 45° being the most accurate and 90° the least (Rubayo et al., 2020). Boyer et al agreed that print orientation does have a significant effect on dimensional accuracy of aligners, but concluded that the 90° orientation was the most accurate, contradicting the findings of Rubayo (Boyer et al., 2021). All of the aforementioned studies, including the present one, utilized a Formlabs printer. The manufacturer's recommendation is to angle objects no more than 30° for best fitting appliances (FormLabs).

Williams et al. directly 3D-printed orthodontic retainers and studied how build angle effects their accuracy. They printed retainers at 15, 30, 45, 60, and 90 degrees on an SLA printer. The printed retainers were scanned for digitization. Accuracy was measured using digital superimposition with the original digital retainer file. They concluded that retainers printed at 15° was the fastest while those printed at 45° was the least expensive. They went on to state that retainers printed at all the angulations tested were accurate within 0.25mm at the canine and molar cusp tips and incisal edge. These were the most accurate areas of the appliances. Conversely, the facial surface of the central incisors was the least accurate, with a discrepancy of 0.263mm to 0.48mm between the original STL file and the one created from the 3D-printed retainers (Williams et al., 2022).

Regarding compression strength, only one study was found to be relevant. Saini et al printed a long rectangular specimen at 0°, 22.5°, 45°, 67.5°, and 90°. They studied various mechanical properties of the printed parts, including compression strength using an Instron machine. They found the largest compressive load was tolerated by the specimen printed at 67.5° (Saini, Dowling, Kennedy, & Trimble, 2020).

This study set out to investigate if print angle influences the compression strength of 3D printed orthodontic aligners, and add to a limit amount publications in this field. Our hypothesis was disproved, and we have found that the orientation of an aligner being printed using an SLA printer does not affect the its compression strength. Orthodontic providers should use this information, as well as data from other studies when deciding how best to angle aligners to ensure they have the most efficient workflow and clinically stable product.

8.0 Limitations

There were some limitations in this study that could be improved in future studies. Firstly, there is no available resin designed for orthodontic aligners. This study used Dental LT Clear V2 resin (Formlabs) which is ideally used for splints and occlusal guards. E-Ortholign is a material by EnvisionTEC that states it is designed specifically for the direct printing of clear orthodontic aligners, but it is currently not available for purchase. Another limitation was the process of creating a digital rendering of an aligner. We were unsuccessful in trying to directly scan an aligner due to its translucency. Currently, Ortho Studio by Maestro 3D is the only software that has the capability to create an aligner from an intraoral scan.

9.0 Future Studies

There are many areas still to be discovered in the world of 3D printed orthodontic aligners. Since it is a practice that has not been clinically implemented yet, there is still plenty of opportunities to increase our understanding of these appliances.

Tensile strength of an aligner is important due to the nature of a patient having to pull on it to remove it from the mouth multiple times per day before eating and tooth brushing. A future study could concentrate on testing tensile strength of 3D printed aligners and making a comparison to aligners that are thermoformed.

Another possible study is to compare how well teeth track during treatment with a 3D printed aligners compared to traditional thermoformed aligners. This would be very valuable clinical information that can save orthodontic providers, and patients, a lot of time if it is shown that one material outperforms the other at moving teeth.

A third study could involve 3D printing aligners using different styles of 3D printers and comparing the mechanical properties of the aligners as well as how well the teeth track using each one.

10.0 Conclusions

1. There was no statistically significant difference in the compression strength of orthodontic aligners printed at 0°, 30°, 60°, and 90°.
2. Aligners printed at 0° had the greatest range of data and were the most inconsistent.
3. Orthodontic providers should use this data along with that from other publications cited here to decide how best to orient aligners for maximum efficiency during 3D printing.

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