EFFECT OF SLOT DIMENSIONS ON ALIGNER RETENTION

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Abstract

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Introduction*:* Orthodontic brackets with rectangular arch wire slots have been historically used for fixed orthodontic treatment and remain as the industry standard. In light of the biomechanical disadvantages of rectangular slot design and the tremendous market demand for clear aligner therapy, a novel orthodontic device system was designed and evaluated. Clear aligner therapy (CAT) as a solo system has another host of compromises and disadvantages which include lesser treatment outcomes and lack of tooth movement accuracy. A novel 3D printed orthodontic trapezoidal slot twin bracket was fabricated to be used as a fixed appliance, as a clear aligner system, and/or a combination of both. Research on this alternative slot form was conducted on aligner retention utilizing varying slot dimensions with the base of slot ranging from 0.014” to 0.018” and top of slot ranging from 0.040” to 0.060”. A 2mm retention attachment and no attachment model were used as an industry comparison/control.

Methods: The trapezoidal slot twin bracket (UL5) was fabricated in composite/ceramic hybrid via 3D printed technology. The brackets were bonded to a 3D printed model and scanned using a Trios 3 intraoral scanner. The STL file was then 3D printed using Sprintray 3D printing technology. A vacuum-form using Zendura Flex aligner material was fabricated on the model using a Ministar S pressure forming machine. The aligner was trimmed equal-gingival. A custom uniaxial tensile testing machine was used to measure the force required to remove the aligner from the testing model.

Results: The data collected was compared to each top of slot dimension (0.040", 0.050", 0.060"), each base of slot dimension (0.014" or 0.018"), no attachment, and 2mm retention attachment. Two-tailed T-tests showed clinical significance among all categories tested. An ANOVA was conducted to confirm clinical significance among the different slot configurations.

Conclusion: From the data collected, researchers were able to select a slot dimension of choice for further testing of the system.

Acknowledgments

I extend my deepest gratitude to Dr. James Mah for guiding me through this project and aiding myself in shaping a research thesis that holds significant relevance in the field of orthodontics. I am eager to witness the unfolding of the potential of this innovative orthodontic appliance in the future.

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Finally, my deepest gratitude goes to my incredible family, especially my wife Rachael, for her unwavering support and sacrifices, which have allowed me to pursue my aspirations and dreams. I owe all of my accomplishments to you!

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Fixed orthodontic appliances have been utilized since their introduction in the past. Despite advancements, many concerns in orthodontics, particularly related to Newton's Third Law of Motion stating that every action (force) in nature has an equal and opposite reaction, continue to persist. The process of wire bending is still necessary for the completion of cases, and the level of precision can vary significantly among practitioners. Achieving accuracy remains challenging, especially when it comes to obtaining proper torque, which affects the final outcome of orthodontic cases. Furthermore, although orthodontic brackets have become smaller, incorporating less metal, they still are perceived as aesthetically unappealing by prospective orthodontic patients.

Several studies have indicated a growing demand for aesthetic alternatives among adult orthodontic patients (Rossini, 2015). Recent research has further highlighted an increased desire and acceptance for esthetic orthodontic treatment options (Alansari, 2019; Alansari, 2020). The conventional approach of using fixed metal brackets and wires is often viewed as unattractive by patients, leading to hesitancy in initiating treatment unless aesthetic alternatives are offered (Alansari, 2019; Rosvall, 2009). The Align Corporate Fact Sheet in Q2 2022 display the current demand for clear aligners through their statistics about Invisalign® (Align Corporate, 2022):

1. Aligners made per/day: 825,000 aligners/day
2. Total aligners shipped: 1.2 billion
3. Invisalign patients to date: 13.4 million

1.1 Historical Background

The development of contemporary fixed orthodontic appliances can be traced back to ancient Egyptian civilization, dating as far back as approximately 3000 BC. However, Pierre Fauchard

(1678-1793), considered the “father of modern dentistry” and “orthodontia,” created significant attention to the field of orthodontics in the development of the bandeauor bandolet in 1723. Edward Angle (1855-1930) referred to as “Father of Modern Orthodontics” developed four different systems: E (expansion) Arch (1900); pin-and-tube appliance (1910), ribbon-arch appliance (1915), and then finally the edgewise appliance (1928). The ribbon-arch appliance (1915) was the first archwire slot, however, it was vertical and had little control of mesial and distal tips of teeth. One of his most meaningful contributions to orthodontics was the transformation of the ribbon-arch appliance (1915) into the edgewise appliance (1928). This innovation involved turning the ribbon-arch appliance 90-degrees, on its edge, to create the edgewise appliance, horizontal rectangular slot geometry. Notably, the edgewise appliance, featuring a slot dimension of 22 x 28 mils, marked a significant milestone as the first orthodontic appliance capable of facilitating simultaneous tooth movement in all three spatial planes. Such was the impact and appeal of the edgewise appliance that it rapidly gained popularity, ultimately becoming the foundation for all modern orthodontic appliances. Over the years, various adaptations and modifications have been made to Angles' edgewise appliance, leading to the development of different appliance variations widely used in contemporary orthodontics.

Some of these variations of the edgewise appliance and treatment modalities began with Charles Tweed (1940), Raymond Begg with Begg appliance (1933), and Peter Kesling with Tip-Edge bracket (1986). Larry Andrews revolutionized the orthodontic market in the development of the Straight-Wire Appliance (SWA) in 1970. The system created a bracket for each individual tooth with built it bracket prescriptions for in/out, tip, and torque to allow a straight wire to be placed without bending wire. This is the current orthodontic bracket rendering on the orthodontic market today with different bracket prescriptions built into the straight wire system such as: Andrews, Ricketts, Alexander, McLaughlin/Bennett/Trevisi (MBT).

The concept of moving teeth using plastic materials is not a recent development. It was described as the "Positioner" in 1946 by Harold Kesling (1901-1979). The positioner appliance was fabricated after the patient was debanded and plaster models were generated. The teeth were then sectioned and set in wax to proper position. From the finalized models in which the teeth were set in proper arch form, axial inclination of the teeth, and interdigitation, a single rubber positioner was fabricated. The rubber positioner occupied the freeway space and covered the surfaces of the maxillary and mandibular teeth. The rubber positioner was to be worn throughout the night and four hours during the day. (Kesling, 1946) Many other practitioners came after Kesling aiding in the development of different thermoform materials, especially with the emergence of vacuum forming technology during the second world war. Nahoum described the use of vacuum formed plastics for nightguards, retainers, oral habit breakers, periodontal splints, and mandibular repositioning splints. (Nahoum, 1964) McNamara worked on different thermoplastic materials that eventually developed the Essix^{TM} material for orthodontic retainers. (McNamara, 1985) Sheridan began utilizing Essix^{TM} to move teeth using block out prior to thermoforming process. (Sheridan, 2004)

However, the formalization of this approach as now known as Clear Aligner Therapy (CAT) gained prominence when Align Technology introduced their product Invisalign® in 1997. The prior techniques were technique sensitive and time-consuming for the practitioner. Invisalign$^{®}$ utilized Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) and stereolithography to create series of clear aligners that moved teeth in a progressive manner to achieve their final planned position. (Kuo, 2003) Since then, Invisalign® has become a widely recognized and commonly employed modality for achieving minor to complex tooth alignment.

1.2 Slot Dimension Variability

As mentioned in the Section 1.1, the historical and current market for orthodontic bracket slot dimension is rectangular, 0.022” x 0.028”. However, the 0.022” x 0.028” is a ballpark figure as a majority of rectangular slot brackets on the market are oversized. In a study that used five upper left central incisor brackets from eleven (11) commercially available bracket systems they found that all bracket slots were oversized and the actual bracket geometry was variable. Three systems were within 5% of stated dimension and one system recorded a slot base oversized of 24%. The slot shapes were variable ranging from straight walls, convergent and even divergent walls. Researchers concluded that inaccurate machining of bracket dimensions and use of undersized wires can limit and affect 3D tooth positioning. (Cash, 2003) A more recent study using Micro-computed Tomography (Micro-CT) found similar results in that all the brackets tested had slot dimensions that were significantly larger than the stated 0.022”. Further, the brackets slots were divergent, 91% asymmetrical at the base and 100% asymmetric at the face of the bracket. The researchers concluded that orthodontists should expect variability of bracket slots from manufacturer specifications and anticipate the shortcomings of each system which will require modification of treatment mechanics. (Alqahtani, 2021) In another study, they found that not just slot base can be affected by manufacturing but slot height can be affected. They found that Speed brackets had a 2% smaller slot height and Damon Q brackets had a 3% increase in height. Interestingly, they found that Damon Q bracket and In-Ovation brackets had less variability due to the near trapezoidal or divergent bracket wall shape. (Major, 2010) Another study looked at slot dimension and analysis of torque expression of three different manufactures. They found similar results to prior studies that due to production tolerance, a difference in real values and nominal values of slot dimensions are extremely common. Due to this production tolerance, torque expression is limited. (Tepedino, 2020) The parallel walls of the 0.022" x 0.028" orthodontic slot make is extremely difficult for manufactures to be precise. The seemingly small tolerance in orthodontic treatment can pose significant challenges for practicing orthodontists, especially during the crucial finishing stages of treatment. In the orthodontic field, even single degrees of movement in tip and torque dimensions are meticulously evaluated. Thus, a system that starts with compromises or inaccuracies can have far-reaching consequences as the treatment progresses, potentially leading to complications later on. This may result in increased treatment duration and longer chair times for patients, causing unnecessary delays and additional efforts for both the orthodontist and the patient.

1.2.1 Slot Dimension Variability and Torque Control

In orthodontic tooth movement, there are three dimensions that orthodontists evaluate. They are characterized as first (1^{st}), second (2^{nd}), and third (3^{rd}) order movements. 1^{st} order or "in and out" are buccal and lingual positions of the teeth. 2^{nd} order or "tip" are mesial and distal inclinations of teeth. 3^{rd} order or "torque" are the buccal or lingual inclinations of the teeth which can be characterized by crown or root torque. 3^{rd} order is the hardest and most challenging movement in orthodontics and is the foundation of many of the new innovations in orthodontic brackets in the finishing phase of treatment. In a study the researchers were evaluating the expression of torque from nine (9) different bracket types with included, passive self-ligation, active self-ligation, twin with stainless steel ties, twin with ligature ties, and twin without ligatures. They found that influence of ligature, active or passive self-ligation mechanics were minimal however, the slot dimension was far more important in the transmission of torque. (Brauchli, 2012) In another study, the researchers evaluated five different system of bracket slot and arch wire dimensions in manufacturer precision and third order, torque expression. They found, the lowest torque loss was SPEED system at 4.5 degrees and highest torque loss was Damon Q at 11.7 degrees. From a prior study, this is anticipated as the Damon was greatly oversized in slot dimension and the speed bracket was undersized in slot dimension. The researchers concluded that manufacturer dimension should not be taken for granted and that detail and finishing will require added torque bends by the orthodontist. (Joch, 2010) Another study looked at amount of force or torquing moments in six different system and found that the ceramic bracket tested had the highest torquing moment whereas the self-ligating system demonstrated 7-fold decrease moment during insertion and 100% increase of torque loss relative to ceramic bracket. (Morina, 2008) These studies clearly demonstrate a need for better manufacturing tolerances as the precision of the slot dimensions are critical in expression of third order or torque expression in an orthodontic bracket system.

1.3 Alternative Bracket Designs

An orthodontic treatment plan typically comprises three phases: (1) level and alignment, (2) space closure, and (3) detail and finishing. In the first phase of level and alignment, all current orthodontic brackets available in the market demonstrate efficient performance. However, when it comes to the second phase of space closure, there are conflicting views within the orthodontic community regarding the best system or its effectiveness due to friction-related issues in these systems.

Interestingly, the majority of "new" bracket systems that enter the orthodontic market claim to enhance efficiency, leading to decreased treatment times during the third phase of treatment, i.e., finishing. These novel systems also boast increased three-dimensional control (in/out, tip, and torque), which contributes to the reduction in treatment duration.

Given the extensive research on slot dimension variability and torque control concerning the conventional rectangular slot dimension, many researchers, orthodontists, and innovators have directed their efforts towards investigating alternative slot dimensions and arch-wire configurations. Pitts21 Pro bracket system (OC Orthodontics, Oregon, USA) utilizes a progressive square slot dimension, 0.021” x 0.021”. The claim is that torque can be expressed earlier in earlier wires due to decreased bracket slot tolerances. The Norris System (Dynaflex, Missouri, USA) utilizes a 0.020” x 0.026” slot dimension, which claims that decreased bracket height allows for more efficient torque control and ease of finishing. Further, the system utilizes a rounded rectangular finishing arch wire that claims to create ease of closure and no compromise in torque control. The Damon Ultima System (Ormco, California, USA) has maintained the same slot geometry, however, they have changed all of the rectangular wires to 0.0275” depths to better aid in three-dimensional control in tip and torque. A study investigated a new slot system and V-wire mechanics with regards to torque. This innovative V-slot system was tested against 0.022” slot. Torque measurements were performed with 0.018’ x 0.025” and 0.019”x 0.025” stainless steel wires in the 0.022” slot groups. The study found similar results with the mechanical disadvantages of rectangular slot form such as “slop” or play with decreased torque expression from the prescription. The study also found that the V-slot system allowed for force reduction and complete seating of the wire due to the divergent pattern of the walls of the bracket. The negative side effect was that beyond 15 degrees of torque added into the wire, the wire twisted out. (Wichelhaus, 2017) Through continual improvement and innovation, finishing and three-dimension control are gradually improving, however, there are still mechanical disadvantages that need to be improved.

1.4 Clear Aligner Biomechanics

Modern day clear aligner treatment begins with an intraoral scan or polyvinyl siloxane (PVS) impressions and bite registration. Along with clinical photos, a treatment plan is created digitally to fabricate a series of intraoral clear aligners, each with a prescribed amount of tooth movement. The aligners or thermoplastic appliances are then thermoformed on 3D printed models and are to be worn by the patient for 20 hours per day for 7-10 days per each set of aligners. (Kravitz, 2009) The aligners are created in stages which each aligner having a limit of 0.25-0.3 mm of tipping movement, 2-3 degrees of rotation, and 1 degree of root torque (Morton, 2016; Kravitz, 2009). In the beginning of modern day clear aligner therapy, very little longitudinal data though research had been collected and analyzed. Treatment plans were mainly driven from clinical experience via trial and error and since the introduction into the orthodontic market, limitations began to appear. (Ling, 2007) Clear aligners can no doubt move teeth however the efficiency and accuracy in which they move to the prescribed amount is in question.

A study compared 48 post-treatment records of orthodontic patients treated with Invisalign® and fixed orthodontics using the American Board of Orthodontics (ABO) Objective Grading System (OGS). The researchers found that the Invisalign® group lost 13 OGS points more than fixed appliance group on average, and the overall OGS passing rate for Invisalign® was 27% lower than that for fixed appliances group. (Djeu, 2005) Again, a call to question how efficient clear aligner therapy is for simple and complex tooth movement.

Some pitfalls of clear aligner therapy include, (1) compliance, (2) clinical protocols, (3) thermoform process, and (4) attachment protocols. Compliance still remains the most critical reason for clear aligner failure or inefficiency. There is no way to truly know how offer a patient is wear there aligners. Patient motivation plays a critical role in achieved prescribed outcome. Like everything in dentistry, clinical protocols are clinician based. There are particular guidelines however, every clinical has different preferences when it comes to the finished product and the means of how to achieve that product or finish. Although clear aligner therapy has come a long way since its modern day inception, clinical protocols for treatment of different malocclusions is still a far cry from seamless. (Morton, 2016; Kravitz, 2009)

Although the thermoforming process has been around for over 50 years, obtaining a uniform thickness of plastic still remains problematic. (Kumar, 2014) Different thickness, can cause different levels of force on different areas depending on the directions in which it was thermoformed. There are many factors that affect the uniform thickness of thermoformed plastic material around models, including (1) height of the models, (2) direction of the model placed in relation thermoformed plastic, (3) angulation of the teeth, and (4) heating element of the thermoformed plastic. Lastly, to aid in programmed tooth movement, attachments or resin bonded attachments, may be prescribed to facilitate the prescribed tooth moment. Different shapes and sizes have been researched to aid in particular tooth movements, however, little is known about clinical efficiency. Further, the clinical protocol of type of resin and bonding protocol, varies from clinician to clinician therefore creating another possible clinical inefficiency.

1.4.1 Clear Aligner Clinical Inefficiencies

As mentioned earlier, the potential of clear aligner therapy (CAT) to reliably and precisely address complex tooth movements has not been demonstrated. Numerous systematic reviews indicate that straightforward actions like tipping, mesial and distal and bucco-lingual directions, tend to exhibit predictability. However, these reviews reveal that regions involving premolars and canines, which possess more rounded tooth shapes, exhibit a considerable decrease in predictability, particularly in rotational movements. Researchers have observed that CAT can effectively achieve predictable outcomes in dental arch alignment, often proving to be quicker for simple, mild, non-extraction-based treatments. Nonetheless, these studies concur that complex movements such as rotations, extrusions, closure of extraction spaces, correction of anterior-posterior and vertical discrepancies, do not demonstrate substantial efficiency with CAT alone (Lombardo, 2017; Rossini, 2015; Papadimitriou, 2018).

Recent research underscores an increasing trend in the predictability of CAT therapy, albeit not without the integration of auxiliaries and heightened usage of tooth attachments. As practitioners continue to employ CAT, they are uncovering its limitations in scenarios like arch expansion, molar distalization, non-extraction alignment for dental arches with over 6mm of crowding, and the strategic use of elastics, interproximal reduction (IPR), and aligner geometries (Rossini, 2020). Despite ongoing improvements in CAT mechanics and protocols, the overall accuracy across all types of tooth movement stands at around 50%, with bucco-lingual crown tipping emerging as the most efficiently controlled movement. Extrusion and canine rotation remain among the least efficient movements for clear aligner therapy, even with the incorporation of auxiliaries like elastics and tooth attachments (Haouili, 2020)

1.5 Research Hypothesis and Specific Aims

1.5.1 Statement of the Problem

The orthodontic market highly values and demands true-to-size orthodontic brackets. There is a strong need for esthetic fixed orthodontic brackets in the industry. Moreover, there is a significant demand for orthodontic systems that accurately achieve prescribed tooth movements in three dimensions. The versatility of a system that can be utilized for both fixed orthodontics and aligners is greatly desired and essential.

1.5.2 Specific Aims

Despite various attempts to create alternative designs for orthodontic systems, many innovators are now challenging the outdated rectangular orthodontic slot design rooted in history. However, some of the newer orthodontic slot innovations, such as the V-slot and square slot designs, have been identified to possess certain clinical weaknesses. Furthermore, the available clear orthodontic bracket alternatives cannot be utilized in conjunction with a clear aligner system. Consequently, our study aims to conduct an in-vitro simulation of various sizes of an alternative trapezoidal orthodontic slot. The primary objective is to assess the potential of different trapezoidal orthodontic slot configurations to serve as effective retention attachments for aligner mechanics. Additionally, we seek to investigate the extent to which the plastic aligner material can flow into or engage with the trapezoidal bracket slot, providing valuable insights for further evaluation.

1.5.3 Research Questions and Central Hypotheses

1. Does no clear aligner attachment differ in the amount of force required to remove the clear aligner compared to different trapezoidal orthodontic slot dimensions?

H0: There is no difference in the amount of retention of a clear aligner between no clear aligner attachment and the different novel orthodontic trapezoidal slot geometries.

HA: There is a difference in the amount of retention of a clear aligner between no clear aligner attachment and the different novel orthodontic trapezoidal slot geometries.

2. Does a 2mm horizontal bevel retention clear aligner attachment differ in the amount of force required to remove the clear aligner compared to different orthodontic slot dimensions?

H0: There is no difference in the amount of retention of a clear aligner between the 2mm horizontal bevel retention clear aligner attachment and the different novel orthodontic trapezoidal slot geometries.

HA: There is a difference in the amount of retention of a clear aligner between the 2mm horizontal bevel retention clear aligner attachment and the different novel orthodontic trapezoidal slot geometries.

3. Does the geometry of different orthodontic slot configurations at top of slot affect amount of force required to remove a clear aligner?

H0: There is no difference between the top of the slot in the novel trapezoidal orthodontic slot geometries and aligner retention.

HA: There is a difference between the top of the slot in the different novel trapezoidal orthodontic slot geometries and aligner retention.

4. Does the geometry of different orthodontic slot configurations at the base of the slot affect amount of force required to remove a clear aligner?

H0: There is no difference between the base of the slot in the novel trapezoidal orthodontic slot geometries and aligner retention.

HA: There is a difference between the base of the slot in the different novel trapezoidal orthodontic slot geometries and aligner retention.

Chapter 2: Materials and Methods

2.1 Provisional Patent- Alternative Bracket Slot Design

A provisional patent application (#63/402,680) was submitted to protect the design of an orthodontic system. The application includes detailed drawings and an outline of the current theory regarding the functionality of the system. (Figure 2.1)

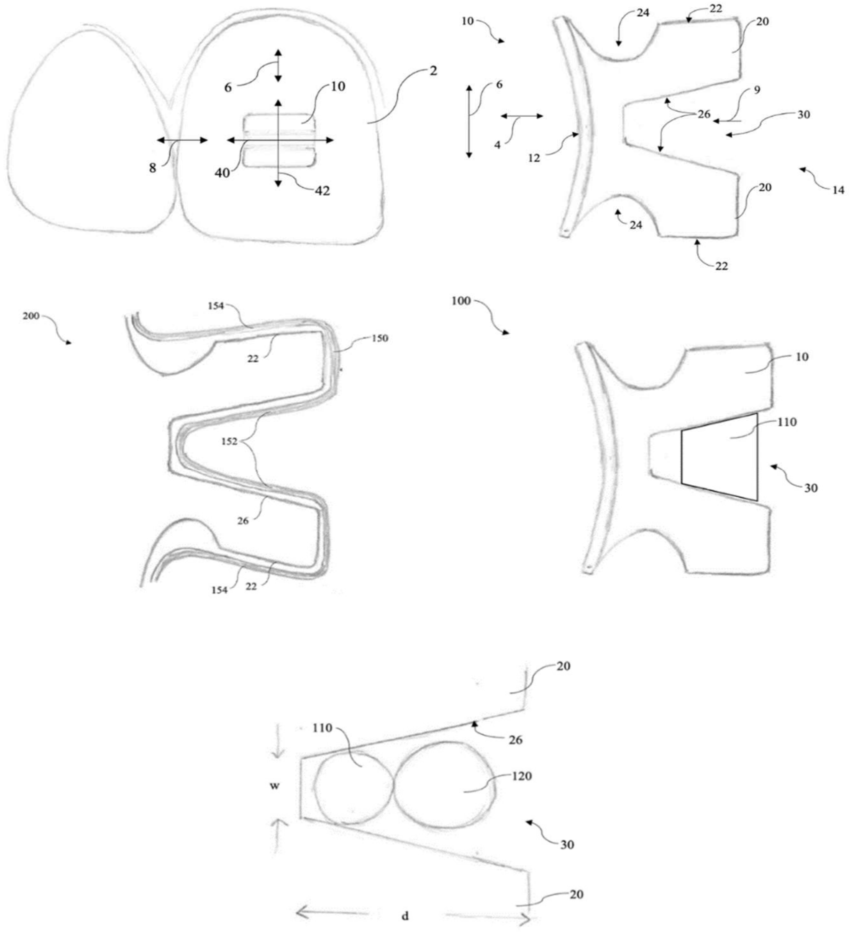


Figure 2.1: Provisional patent drawings of novel trapezoidal slot and theoretical orthodontic system functionality

2.2 Fabrication of Pre-Testing Models

Prior to orthodontic bracket fabrication, preliminary testing was completed to see if an aligner would adhere inside a trapezoidal or divergent slot.

2.2.1 Trapezoidal Slot Model

A trapezoidal slot with varying dimensions was designed in CAD (computer aided design) using SolidWorks software (Dassault Systems, MA, USA). The base of the slot had dimensions of 0.014”, 0.018”, 0.020”, and 0.022”, while the top of the slot had dimensions of 0.040”, 0.050”, and 0.060”. This resulted in twelve different combinations for testing: 0.014” x 0.040”, 0.014” x 0.050”, 0.014” x 0.060”, 0.018” x 0.040”, 0.018” x 0.050”, 0.018” x 0.060”, 0.020” x 0.040”, 0.020” x 0.050”, 0.020” x 0.060”, 0.022” x 0.040”, 0.022” x 0.050”, and 0.022” x 0.060”. The height of all configurations was 0.035”. (Figure 2.2) The model was printed using a SprintRay Pro95 3D digital light processing (DLP) printer (Sprintray Inc., CA, USA) (Figure 2.3). The Keyprint KeyModel Ultra^{TM} (Keystone Industries, Myerstown, PA) resin was used to replicate the orthodontic structure. The printing settings were set to 50-microns per slice height to produce a finer final model. After printing, the model was removed from the build platform and soaked in 99% isopropyl alcohol for 15 minutes, followed by air-drying. Curing was done in accordance with the manufacturer's recommendations using the MoonRay Pro Cure (Sprintray Inc., CA, USA), for a duration of 15 minutes. Subsequently, the model was positioned horizontally on a MiniStar S pressure forming machine (Great Lakes Orthodontics, Tonawanda, NY) (Figure 2.4) with the grooves facing horizontally. Two models were set on pressure forming machine, one model with 0.040” top of slot positioned vertically and then one with 0.060” top of slot positioned vertically. The aligner material used was Zendura FLX® (Bay Materials LLC, Fremont, CA, USA), which is a multi-layer copolyester-polyurethane composite. Once the aligner was vacuum-formed onto the models, it was trimmed and visually inspected to ensure a fit and fill of thermoformed plastic within the grooves of the different slot dimensions. (Figure 2.5)

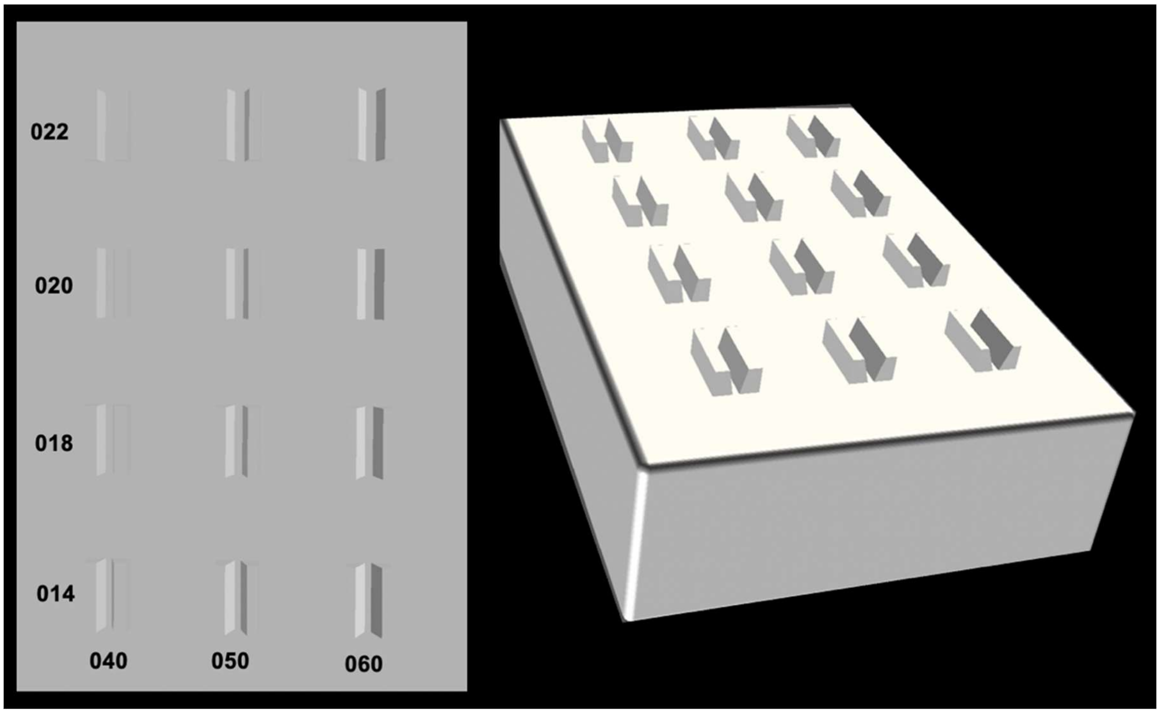


Figure 2.2: CAD design of twelve (12) slot configurations

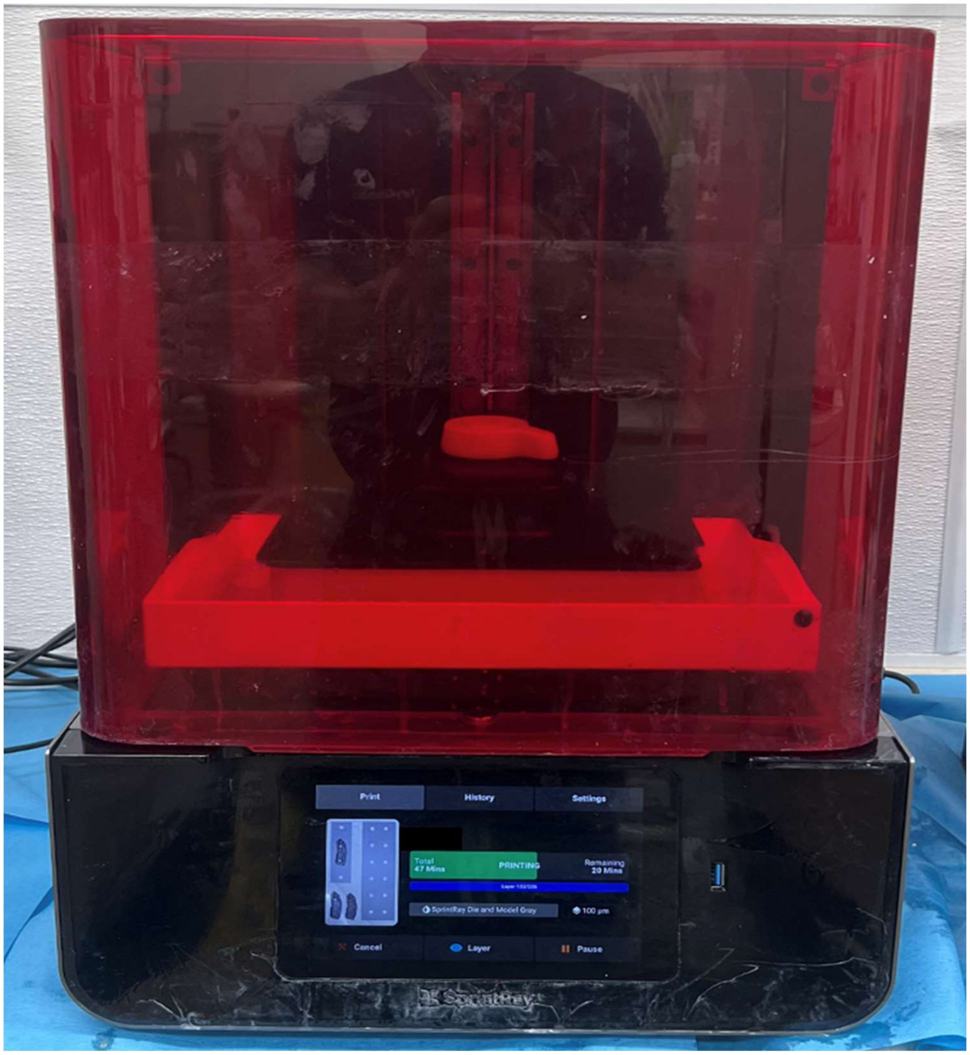


Figure 2.3: SprintRay Pro95 3D digital light processing (DLP) printer use to fabricate all models during investigation

Figure 2.4: MiniStar S pressure forming machine used during entire investigation for fabrication of vacuum-formed aligners

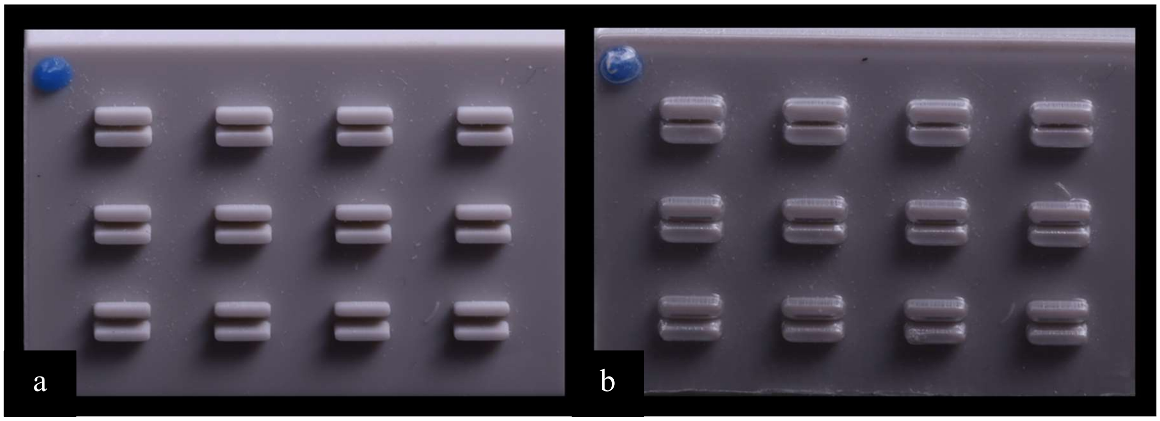


Figure 2.5: a) 3D printed resin model b) Model with vacuum-formed Zendura Flex

2.2.2 Fabrication of Testing Model

To verify the suitability of each slot dimension for retaining an aligner material, a series of retention tests were conducted using a uniaxial testing unit. For this purpose, a new SolidWorks (Dassault Systems, MA, USA) model was generated, incorporating each slot dimension on a 10 mm x 10 mm x 10 mm square platform with a top access hole 8mm x 8mm x 5 mm in dimension. In order to ensure secure attachment to the uniaxial testing unit, a solid base measuring 55 mm x 30 mm x 10 mm was incorporated to the testing model. Two 6 mm holes were precisely positioned in the base, with a center-to-center distance of 30 mm, to allow for screw fixation to the base of the uniaxial testing machine. This addition provided a stable and reliable connection between the model and the testing unit, facilitating accurate and consistent testing procedures. The subsequent steps for 3D printing the testing model followed the precise instructions outlined in Section 2.2.2. Before vacuum-forming, a PVS material was inserted into the recessed hole of each testing model measuring 8mm x 8mm x 5 mm. Subsequently, each individual testing model with its respective slot dimension was positioned on the MiniStar S pressure forming machine (Great Lakes Orthodontics, Tonawanda, NY). A sheet of Zendura FLX® (Bay Materials LLC, Fremont, CA, USA) was then vacuum-formed over each testing model. Following this process, the aligner was carefully removed, trimmed, and a pilot hole was drilled at the center of the aligner's top surface to enable placement of a screw for setting up the uniaxial tensile unit. (Figure 2.6)

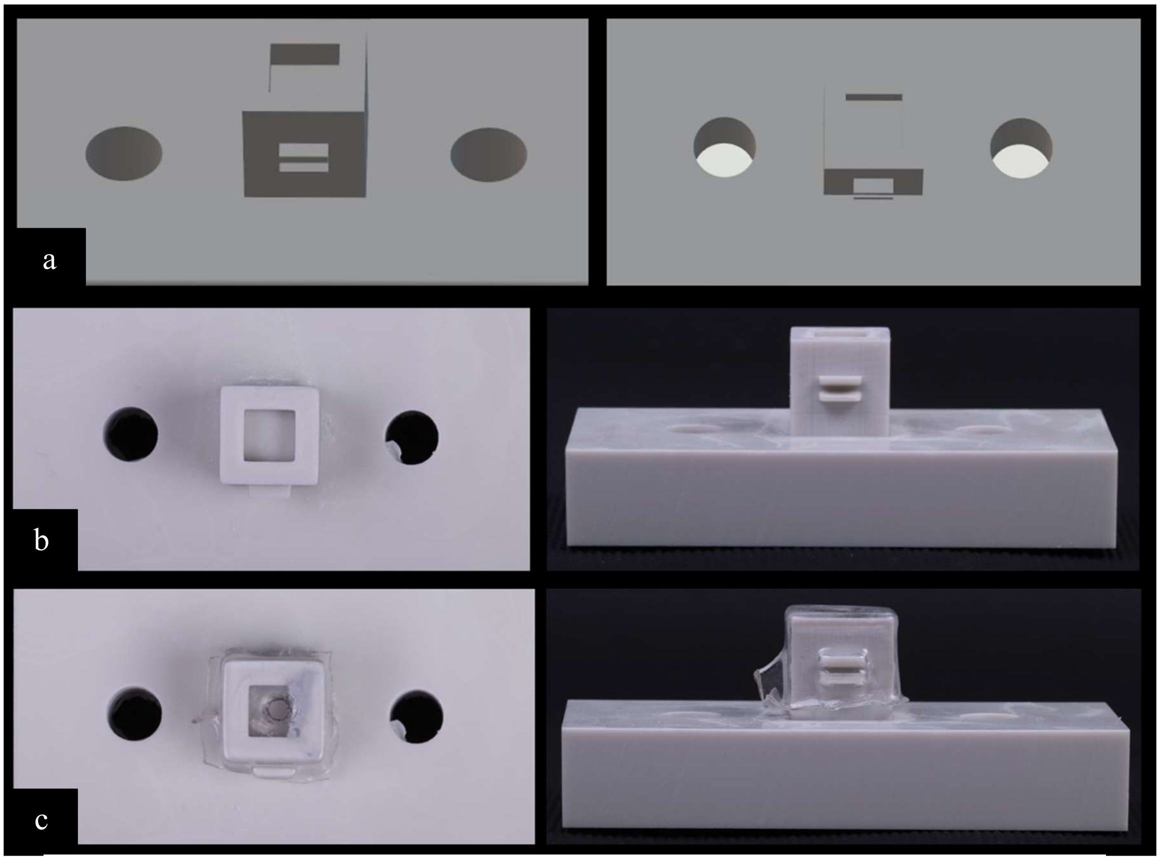


Figure 2.6: a) CAD model b) 3D printed resin model c) Model with trimmed vacuum-formed Zendura Flex aligner with screw access hole

2.2.3 Uniaxial Tensile Testing Setup

To secure the individual models representing each slot dimension, they were firmly attached to the base of the uniaxial testing unit using screws. A square-headed nut was inserted into the access hole of each model and passed through the pilot hole of the aligner. The aligner was then positioned onto the fixed model, aligning the male end of the screw with the pilot hole. The male end of the screw was securely fastened to the load cell to sense the force data. For data acquisition and analysis, a National Instruments (NI) cDAQ system was used to interface with the machine's load cell and displacement control. Using LabVIEW, a software code was developed to pull the aligner off of the fixed model at a constant rate of 0.05mm/s, during which the software also recorded the force data corresponding to the displacement occurring. The force measurements were recorded in pounds (lbs.). To ensure reliable results, two trials were conducted for each slot dimension. This approach aimed to narrow down the range of slot dimensions for future testing and analysis. (Figure 2.7)

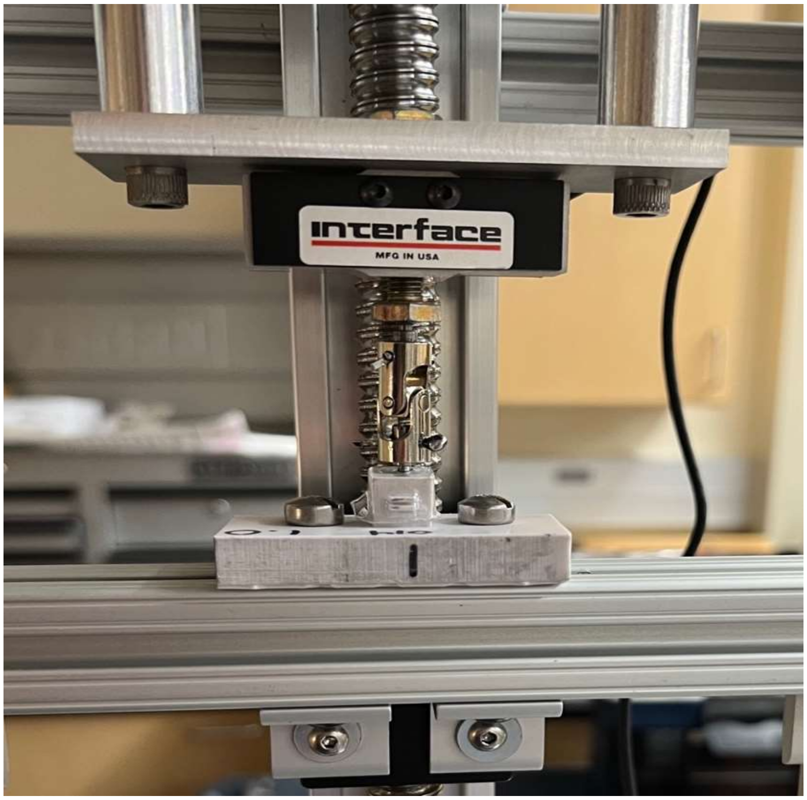


Figure 2.7: Uniaxial testing unit with testing model secured into place onto the platform and screw engaged into the load cell through aligner access hole.

2.3 Fabrication of Orthodontic Bracket and Prescription

Based on the data obtained and analyzed during the pre-testing phase, six slot dimensions were chosen for further examination. The base of slots with the dimensions of 0.020” and 0.022” distributed increased levels of force that would be unable for patient to remove aligner from oral environment. (Table 2.1) The selected trapezoidal slot dimensions were as follows: 0.014” x 0.040”, 0.014” x 0.050”, 0.040” x 0.060”, 0.018” x 0.040”, 0.018” x 0.050”, and 0.018” x 0.060”. It should be noted that the bracket base and bracket heights remained constant for each slot dimension. To proceed with the next phase, the specifications were directed to the bracket design company. (CDB Corporation, Leland, NC). They were responsible for generating computer-rendered designs and manufacturing the brackets accordingly. The prescribed bracket design followed the Roth system with -7° torque, 0° angulation, and 0° rotation. Distal occlusal identification markers were positioned on the bracket tie wings for easy identification (Figure 2.8). The material used to fabricate the brackets, a ceramic-filled methacrylate-based resin, is proprietary to the orthodontic bracket manufacturer (CDB Corporation, Leland, NC). The brackets were produced using a 3D printing process, ensuring high precision and accuracy in their construction (Figure 2.9).

Table 2.1: Data from preliminary slot configuration testing

SIZE	**FORCE (LBS)**	**AVG. FORCE (LBS)**	**SIZE**	**FORCE (LBS)**	**AVG. FORCE (LBS)**
14			**18**		
014_040_T1	2.06		018_040_T1	4.05	
014_040_T2	1.88	***1.97***	018_040_T2	2.08	***3.06***
014_050_T1	5.92		018_050_T1	6.40	
014_050_T2	5.79	***5.86***	018_050_T2	5.70	***6.05***
014_060_T1	5.11		018_060_T1	8.19	
014_060_T2	5.48	***5.29***	018_060_T2	6.19	***7.19***
20			**22**		
020_040_T1	3.36		022_040_T1	6.41	
020_040_T2	4.58	***3.97***	022_040_T2	6.04	***6.23***
020_050_T1	4.63		022_050_T1	9.32	
020_050_T2	7.29	***5.96***	022_050_T2	8.44	***8.88***
020_060_T1	6.47		022_060_T1	4.09	
020_060_T2	*1.67*	***6.47***	022_060_T2	3.89	***3.99***

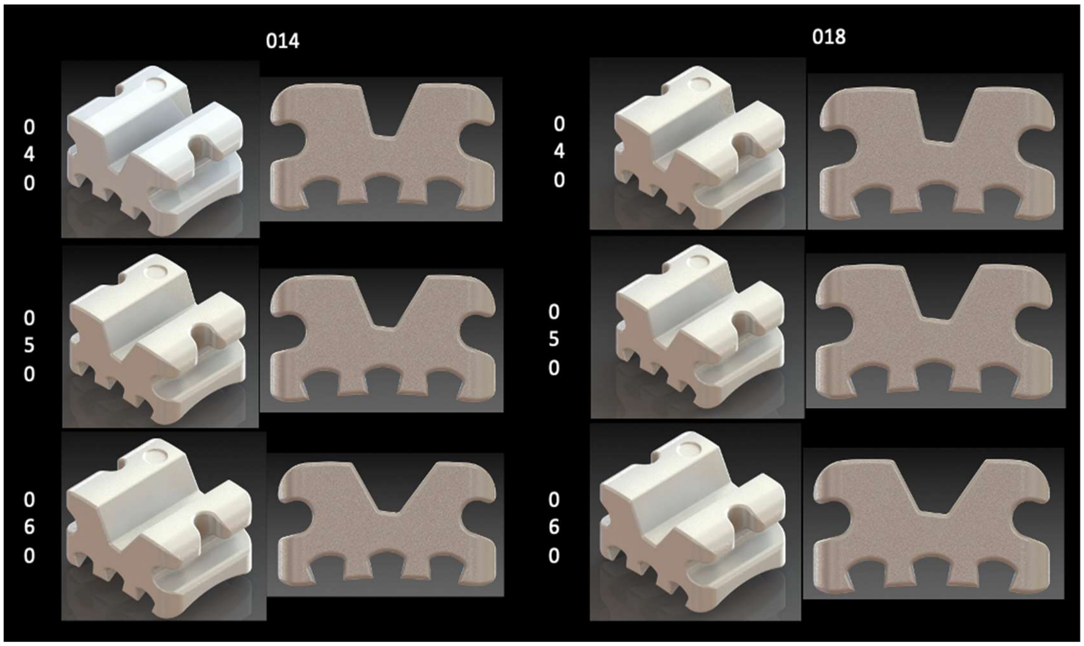


Figure 2.8: UL5 CAD renderings of each testing trapezoidal bracket slot configuration

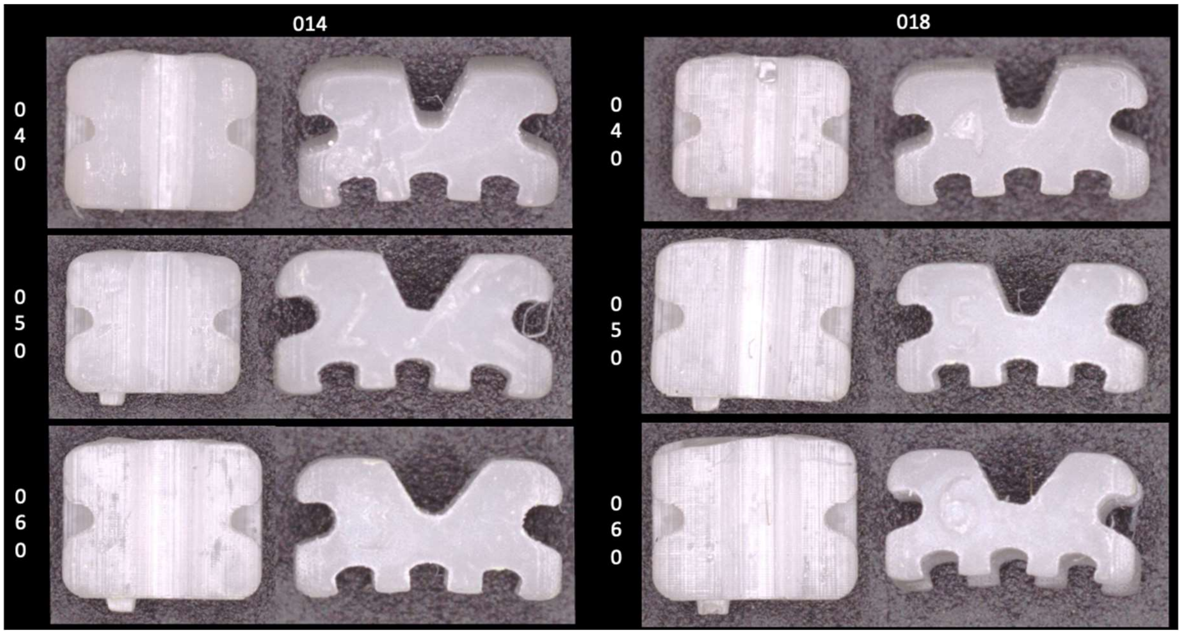


Figure 2.9: 12x magnification of 3D printed testing models

2.4 Fabrication of the Pre-Treatment Model (Master Model)

The pre-treatment model used in this study was from Kilgore 200 typodont (Kilgore International, Coldwater, MI). The upper left quadrant was scanned using 3Shape TRIOS^{TM} intraoral scanner (3Shape, Copenhagen K, Denmark). The stereolithography file was transferred to uLab orthodontic software (uLab Systems, Memphis, TN) to standardized the master model. The final model was printed using a SprintRay Pro95 3D digital light processing (DLP) printer (Sprintray Inc., CA, USA) . The Keyprint KeyModel Ultra^{TM} (Keystone Industries, Myerstown, PA) resin was used to replicate the orthodontic structure. (Figure 2.10) The subsequent steps for 3D printing the master model followed the precise instructions outlined in Section 2.2.2.

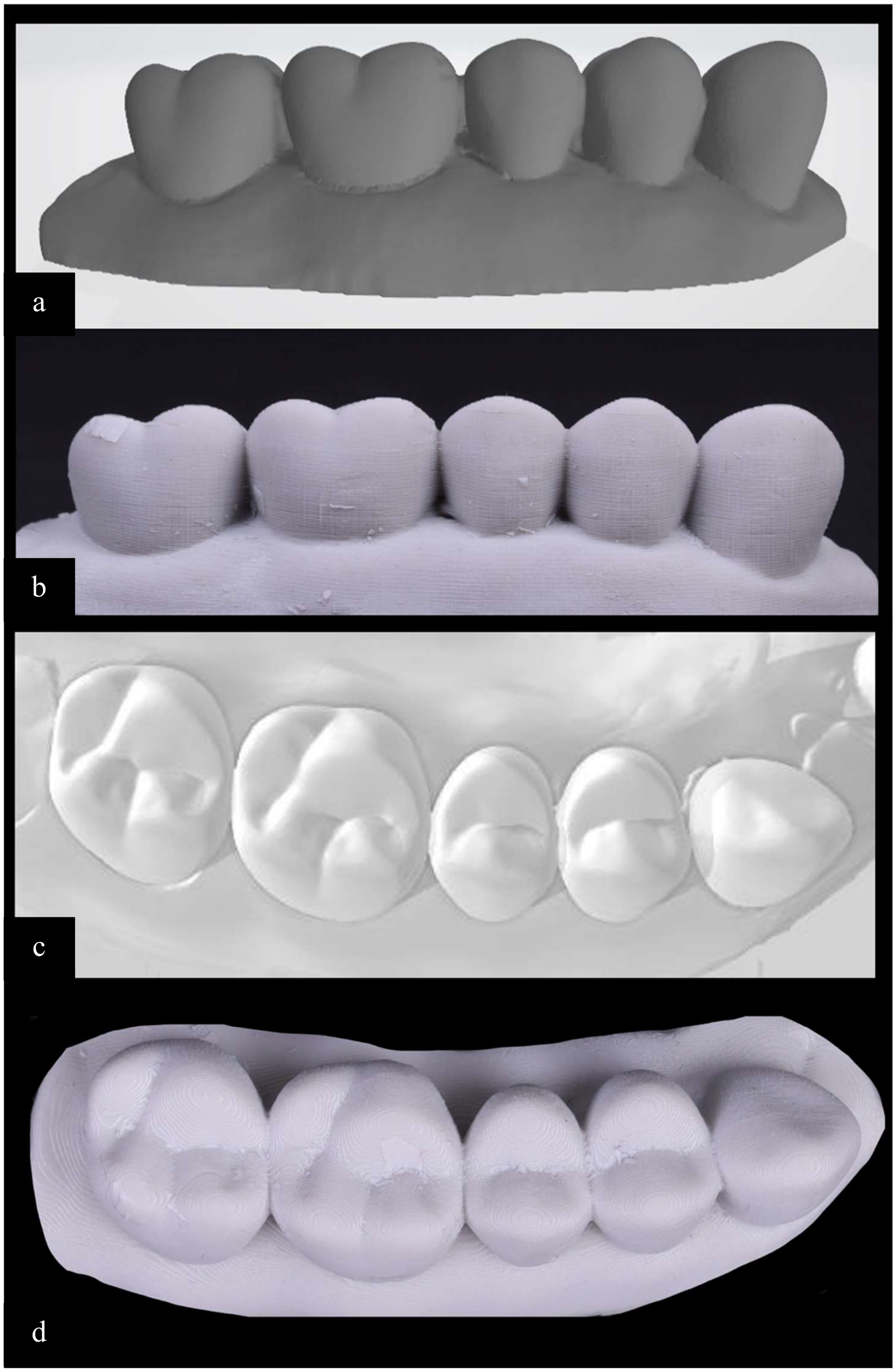


Figure 2.10: a) CAD design of master model side view, b) 3D printed resin master model side view, c) CAD design of master model occlusal view d) 3D printed resin master model occlusal view

2.5 Fabrication of the Testing Model

The master model was manipulated to enable precise bonding of the bracket specimen. A 4.5 mm x 3 mm x 1 mm square was positioned at the FA point of the tooth, 4 mm to center from the buccal cusp tip, ensuring consistent bracket placement across all testing dimensions. To accommodate the screw head, specific holes were strategically positioned on the occlusal surfaces of teeth #15 (UL7) and #12 (UL4). These holes were created with a diameter of 4 mm and were spaced 25 mm apart, aligning precisely with the custom jig mount on the uniaxial testing machine. To secure the testing model to the base of uniaxial testing unit, a 10 mm x 10 mm x 8 mm rectangular mount was employed, featuring two holes placed at 90 mm distance (Figure 2.11). The model was then produced using the same process described in section 2.2.2, utilizing 3D printing technology. A total of eight testing models were printed for each dimension 0.014” x 0.040”, 0.014” x 0.050”, 0.040” x 0.060”, 0.018” x 0.040”, 0.018” x 0.050”, 0.018” x 0.060”, control of 2 mm horizontal retention attachment and no attachment.

Once the physical models were created, the square insert on the buccal surface of tooth #13 (UL5), where the bracket was to be bonded, underwent bonding preparation. The surface was sandblasted with aluminum oxide and a hole was drilled at the center of the insert using a #330 bur, reaching the appropriate depth for cement recess. Subsequently, the prepared surface was etched with 37% phosphoric acid for 30 seconds, thoroughly rinsed, and air-dried. Assure Plus (Reliance Orthodontic Products, Itasca) was applied onto the surface, thinned with air, and light cured. Orthodontic bracket cement, Transbond XT (3M, Maplewood, MN), was placed on the bracket base of the corresponding slot dimension, then inserted into the FA point on tooth #12 (UL5). Excess cement was removed, and the bracket cement was cured for 20 seconds, followed by an additional 5 seconds from the occlusal, mesial, gingival, and distal directions. This preparation process was repeated for each orthodontic bracket slot dimension testing model. (Figure 2.12)

The control 2 mm horizontal retention attachment model underwent an identical preparation process. Using uLab orthodontic software (uLab Systems, Memphis, TN) a current industry standard 2mm horizontal retention attachment was placed on testing model. The attachment model was printed using same protocols in Section 2.2.2. The attachment model was placed onto the MiniStar S pressure forming machine (Great Lakes Orthodontics, Tonawanda, NY), and an attachment template was fabricated using copyplast aligner material (NFJONA, TIO, TIO). Transbond XT (3M, Maplewood, MN), was applied to the attachment template and bonded onto the testing model using the same protocol as above. Overall, these steps were taken to ensure precision and consistency in the bonding and preparation of the testing models for subsequent retention analysis.

Figure 2.11: 3D printed testing model prior to bracket placement
a) occlusal view b) side view

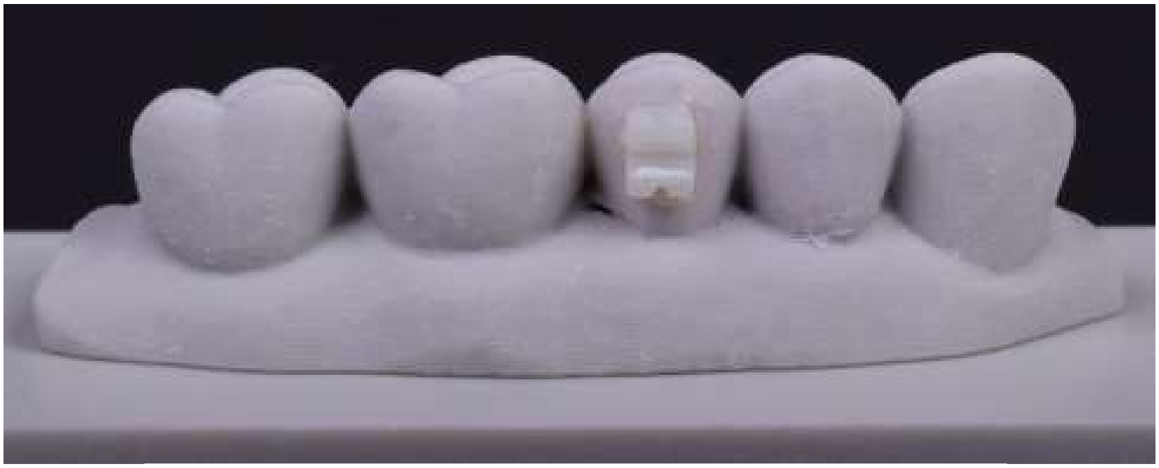


Figure 2.12: 3D printed testing model with bonded UL5 bracket

2.6 Fabrication of the Study Models and Testing Aligners

In line with current market trends and anticipated future protocols, a digital scan was performed for each finalized testing model using the Trios3 intraoral scanner (3Shape, Copenhagen, Denmark). These scans were then transferred to the SprintRay Pro95 3D printer (SprintRay Inc., CA, USA), for the production of study models corresponding to each slot configuration. The 3D printing process followed the precise instructions provided in Section 2.2.2 to ensure consistency and accuracy. This process ensured that for each slot configuration, the bracket within the aligner was in the identical position as the testing model. Subsequently, a single sheet of Zendura FLX® (Bay Materials LLC, Fremont, CA, USA), was vacuum-formed over each study model to create the testing aligners.

Once formed, the aligners were removed from the study models. A straight-line trim was performed along the buccal and lingual gingival margins of the aligners, ensuring a uniform and consistent presentation. Additional trimming was completed above the height of contour at the distal of #15 (UL7) and mesial of #11 to decrease undercut engagement. To prepare for the uniaxial testing machine, pilot holes were drilled through the occlusal surface of the aligners at the positions of #15 (UL7) and #12 (UL4). These pilot holes would allow for the insertion of screws, which would be secured in the jig of the uniaxial testing machine. With these model preparations completed, the aligners were now ready to be attached to the testing model for retention trials. (Figures 2.13 & 2.14)

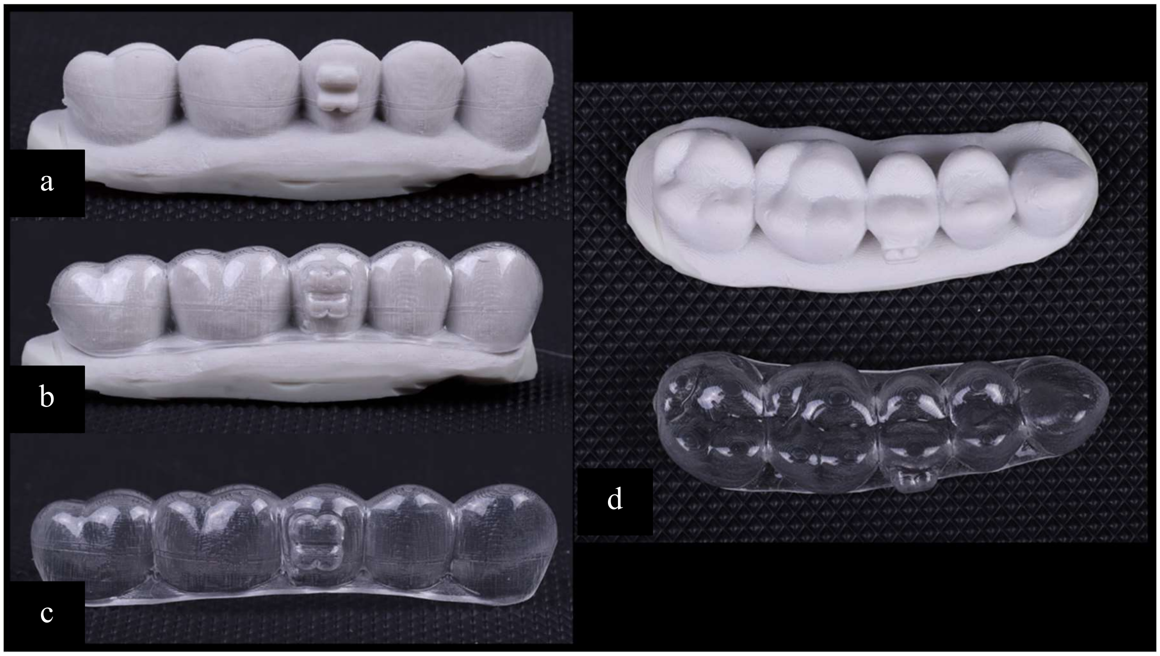


Figure 2.13: a) 3D printed working model b) Zendura Flex attached on working model c) Zendura Flex aligner d) 3D printed working model and Zendura Flex aligner

Figure 2.14: Final testing model with UL5 bracket bonded

2.7 Conducting Trials- Uniaxial Tensile Unit

A dedicated jig was fabricated specifically for the uniaxial testing device to securely attach the testing model and aligner. This jig ensured that the pulling force was applied directly and vertically to the aligner. The testing model was firmly secured to the base of the uniaxial testing device using two screws. Additionally, two screws were inserted through the intaglio surface of the aligner, with the female end of the screws oriented in the vertical direction. The aligner was placed onto the testing model, and the screw heads fit into recessed areas without binding on the occlusal surface of the testing model. The female ends of the screws were then fastened securely into the top jig using two side screws. (Figure 2.15 & 2.16) A total of seventy (70) trials were conducted for each of the eight configurations. The severity of the trials aimed to simulate a 14-day aligner treatment staging, where the aligners were removed and seated an average of five times per day.

For data acquisition and analysis, a National Instruments (NI) cDAQ system was used to interface with the machine's load cell and displacement control. Using LabVIEW, a software code was developed to pull the aligner off of the fixed model at a constant rate of 0.05mm/s, during which the software also recorded the force data corresponding to the displacement occurring. The force measurements were recorded in pounds (lbs.).

Figure 2.15: Testing aligner positioned on final testing model

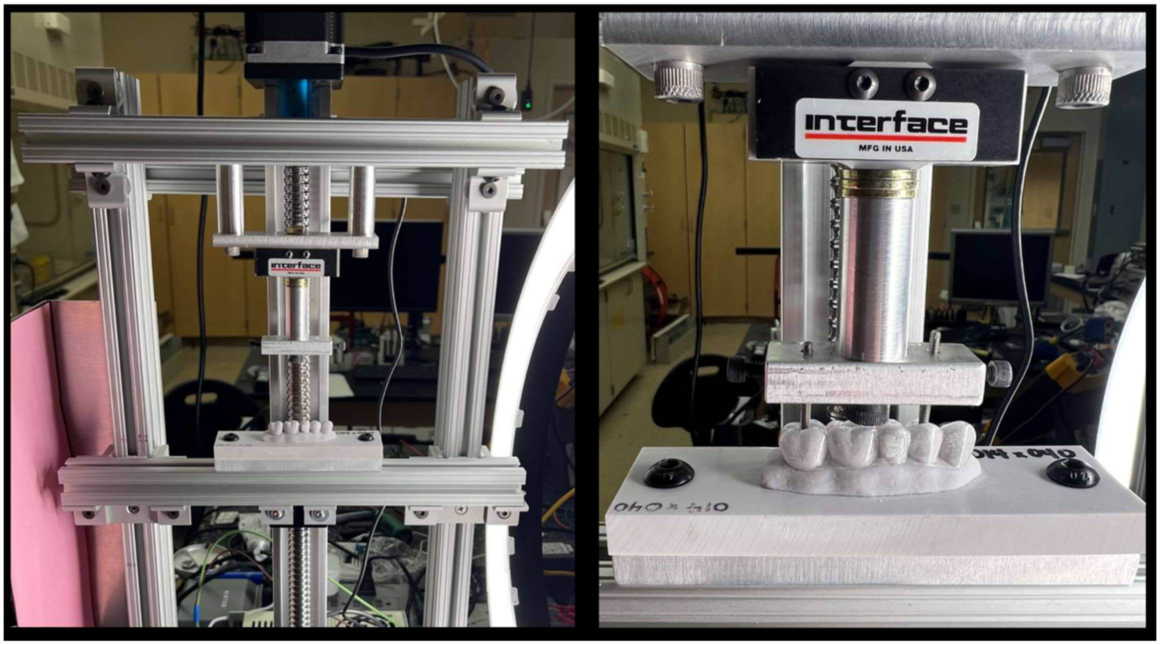


Figure 2.16: Uniaxial tensile testing machine with custom jig. a) testing model secured to base platform b) Aligner placed on testing model and screws secured into top custom jig

2.8 Statistical Analysis

The recorded data from each trial was entered into Excel and saved individually for analysis. For each testing model, the peak force (in pounds, lbs) observed during the trials was recorded and carefully documented. In order to assess the variability and central tendency of the data, the standard deviation and mean were calculated. To determine the statistical significance of the findings, two-tail t-tests were performed. The comparisons were made between the different base dimensions of the slot. Similarly, the top dimensions of the slot were compared to one another. Additionally, each slot dimension was compared to the control groups, namely, the no attachment condition and the 2 mm horizontal retention attachment. Comparative analyses were also conducted between the two control groups, the 2 mm horizontal attachment, and the no attachment condition. A significance level of p-value 0.05 was established to determine statistical significance. To further validate the results obtained through t-tests, an analysis of variance (ANOVA) was conducted. The ANOVA analysis helped confirm the findings of the two-tail t-tests, providing a comprehensive statistical assessment of the data.

2.9 Photograph of Axial Cuts of Alternative Slot Forms

New aligners were created from each slot dimension study model, and subsequently placed on each corresponding the testing model. To analyze the interaction between the aligners and the alternative slot form, the testing model was bisected along the bracket's center using a straight hand piece and Brassler IPR disc. Visual documentation of the plastic molding into the alternative slot shape was achieved by capturing photographs using digital microscope. (VR-3100, Keyence, Japan) at 12x magnification and 25x magnification. (Figure 2.17 & 2.18)

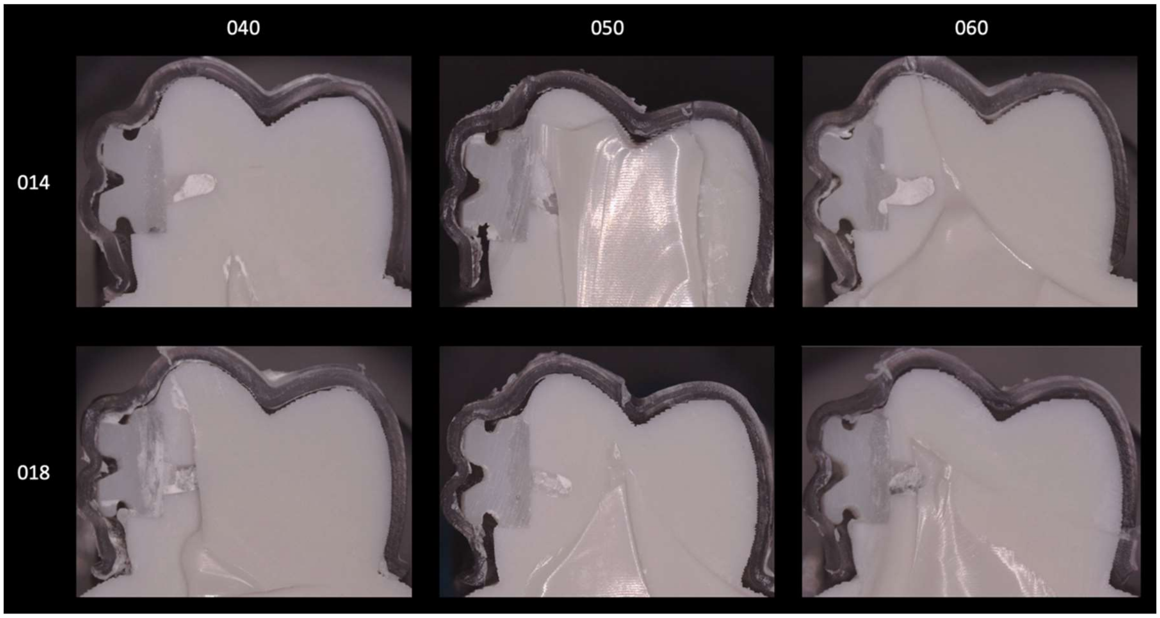


Figure 2.17: 12x magnification of novel orthodontic bracket slots with post vacuum-formed Zendrua Flex aligners to observe aligner engagement in bracket slot

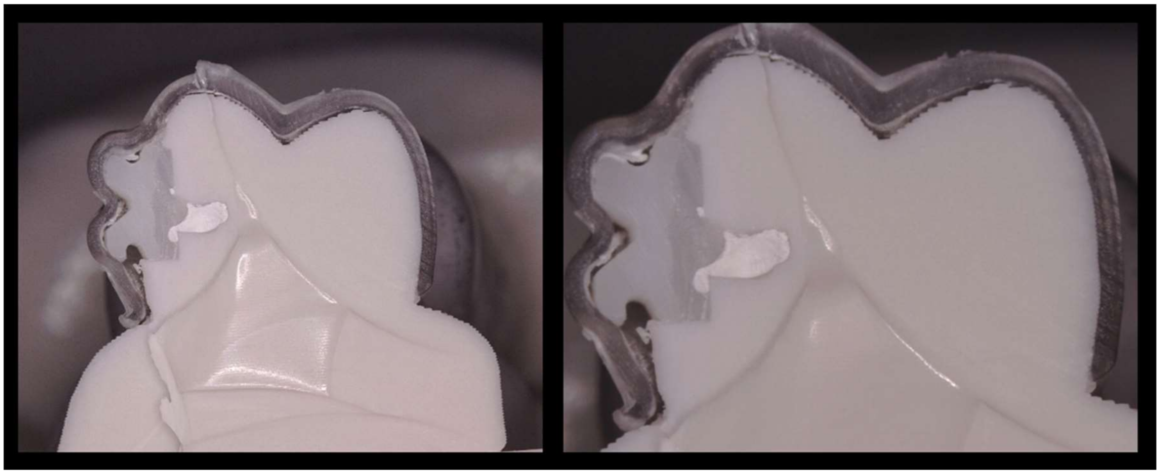


Figure 2.18: 0.014” x 0.060” bracket in cross-section with vacuum-formed Zendura Flex a) 12x magnification b) 25x magnification

Chapter 3: Results

3.1 Average Force Required to Remove Aligner from Model

The mean force in pounds (lbs) of the seventy (70) trials were measured from each configuration. Standard deviations were calculated to evaluate the amount of variation or dispersion of the force required to remove the aligner from the model in the fourteen (14) day, removing five (5) times per day, aligners wear model. The highest mean force was found in the 0.018" x 0.060" trapezoidal slot group, which had a mean of 5.77 lbs of peak force. The lowest mean force was found in the 0.014" x 0.050" trapezoidal slot group, which had a mean of 3.19 lbs of peak force. The highest standard deviation was found in the 0.018" x 0.050" trapezoidal slot group, which had a standard deviation of 0.97. The lowest standard deviation was found in the 0.014" x 0.050" trapezoidal slot group, which had a standard deviation of 0.35 lbs. The current aligner market 2 mm horizontal bevel retention attachment had a mean peak force of 3.60 lbs +/- 0.70 lbs. which was very similar to the 0.014" x 0.060" trapezoidal slot group which had a mean peak force of 3.50 lbs. +/- 0.73 lbs. The no attachment and traditional 2mm horizontal bevel attachment groups were considered our controls within the experiment as they are currently being used on the orthodontic market. (Table 3.1) The clinical application of these findings will be discussed in Chapter 4 Discussion.

Table 3.1: Mean force and standard deviation for each slot configuration, 2mm horizontal bevel retention attachment, and no attachment. Mean force for 70 cycles, replicating 14-day wear with removal of aligner 5 times per day.

Slot Configurations	Mean Force (lbs.)	Standard Deviation
014_040	3.22	0.45
014_050	3.19	0.35
014_060	3.50	0.73
018_040	3.76	0.70
018_050	3.59	0.97
018_060	5.77	0.62
2mm Attachment	3.60	0.69
No Attachment	4.37	0.52

3.2 T-Tests

A paired two-tail t-tests were calculated between all different categories with a clinical significance value set at p= 0.05. Tests were calculated to if statistical significance between base of trapezoidal slot (0.014” and 0.018”), top of trapezoidal slot (0.040”, 0.050”, 0.060”), no attachment, and 2 mm traditional retention attachment. The no attachment and traditional 2mm horizontal bevel attachment groups were considered our controls within the experiment as they are currently being used on the orthodontic market. In the top of slot group with 0.014” base, statistical significance was discovered between the 0.040” vs. 0.060” and 0.050” vs. 0.060” groups. The top of slots group with 0.018” base also demonstrated statistical significance between the 0.040” vs.

0.060” and 0.050” vs. 0.060” group. The 0.014” base and 0.018” base groups vs. no attachment control group, all top of slot dimensions displayed statistical significance. The 0.014” base group vs. 2 mm attachment displayed clinical significance in the 0.040” and 0.050” top of slot but not in the 0.060” group. The 0.018” base group vs. 2 mm attachment group also displayed statistical significance in the 0.040” and 0.050” top of slot groups, but not the 0.060” top of slot group. Lastly, top of slot groups were compared against base of slot, statistical significance was seen in the 0.040”, 0.050”, and 0.060” top of slot group. Further, there was a statistically significant demonstrated between the 2 mm retention attachment and the no attachment groups.

Table 3.2: Two-tailed T-tests. P value <0.05

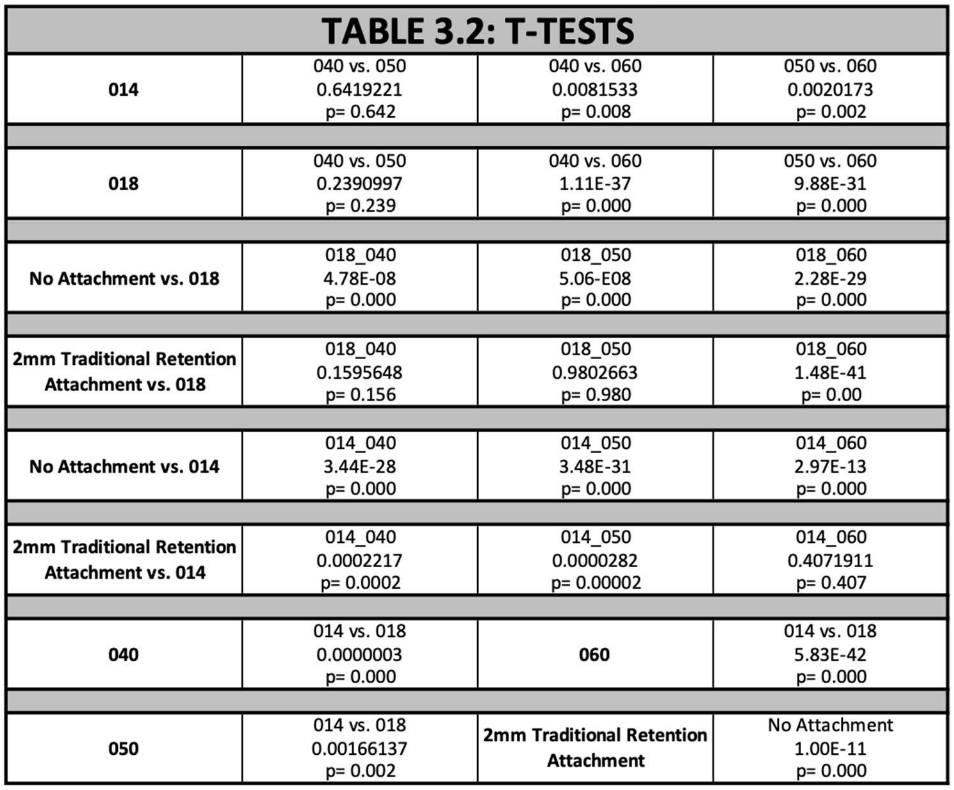


TABLE 3.2: T-TESTS			
014	040 vs. 050 0.6419221 p= 0.642	040 vs. 060 0.0081533 p= 0.008	050 vs. 060 0.0020173 p= 0.002
018	040 vs. 050 0.2390997 p= 0.239	040 vs. 060 1.11E-37 p= 0.000	050 vs. 060 9.88E-31 p= 0.000
No Attachment vs. 018	018_040 4.78E-08 p= 0.000	018_050 5.06-E08 p= 0.000	018_060 2.28E-29 p= 0.000
2mm Traditional Retention Attachment vs. 018	018_040 0.1595648 p= 0.156	018_050 0.9802663 p= 0.980	018_060 1.48E-41 p= 0.00
No Attachment vs. 014	014_040 3.44E-28 p= 0.000	014_050 3.48E-31 p= 0.000	014_060 2.97E-13 p= 0.000
2mm Traditional Retention Attachment vs. 014	014_040 0.0002217 p= 0.0002	014_050 0.0000282 p= 0.00002	014_060 0.4071911 p= 0.407
040	014 vs. 018 0.0000003 p= 0.000	**060**	014 vs. 018 5.83E-42 p= 0.000
050	014 vs. 018 0.00166137 p= 0.002	**2mm Traditional Retention Attachment**	No Attachment 1.00E-11 p= 0.000

3.3 ANOVA

Two-tailed T-Tests were verified using One-Way ANOVA. The F-statistic in the 0.014” group was 75.6167 calculating a P-value of 0, indicating the statistical significance between the groups. The F-statistic in the 0.018” group was 130.8949 calculating a P-value of 0, indicating there is a statistical significance between the groups.

Table 3.3: ANOVA

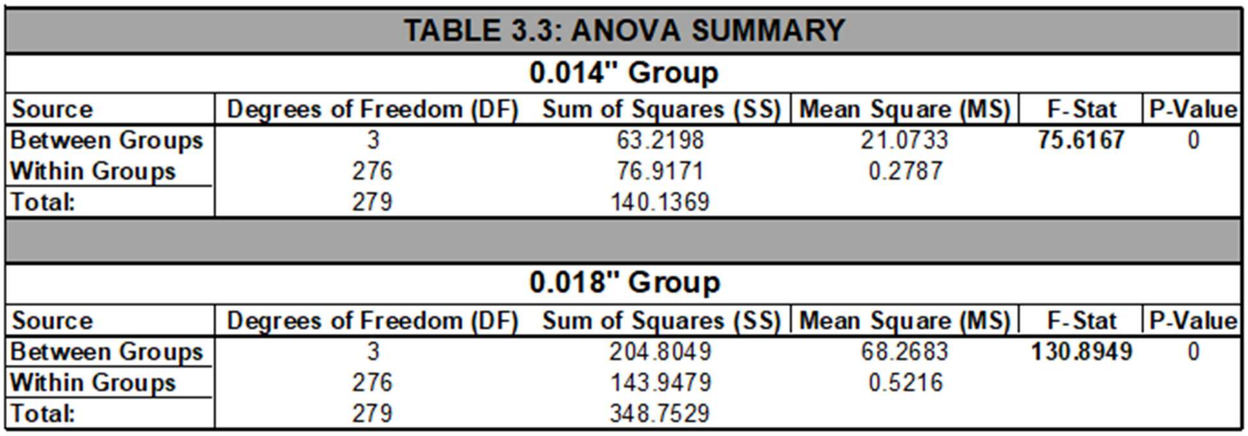


TABLE 3.3: ANOVA SUMMARY

0.014" Group

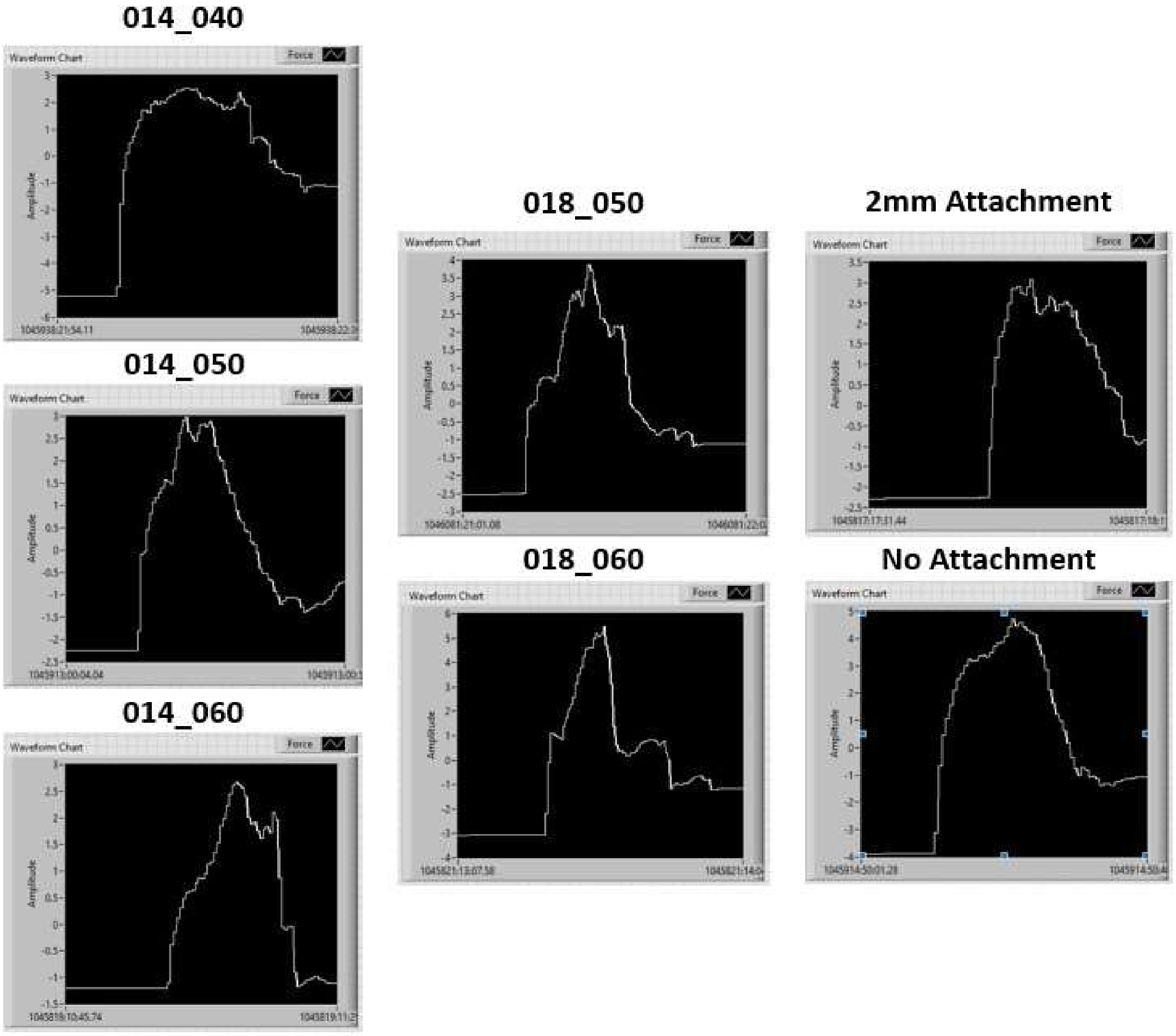
Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F-Stat	P-Value
Between Groups	3	63.2198	21.0733	**75.6167**	0
Within Groups	276	76.9171	0.2787		
Total:	279	140.1369			

0.018" Group

Source	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F-Stat	P-Value
Between Groups	3	204.8049	68.2683	**130.8949**	0
Within Groups	276	143.9479	0.5216		
Total:	279	348.7529			

3.4 Plastic Characteristics on Instron Unit

At trial #35, a screenshot was taken to demonstrate the force pattern to remove the aligner from the model in each testing group. 0.018” x 0.040” group was not captured as it was missed during the trials.


014_040

014_050

014_060

018_050

018_060

2mm Attachment

No Attachment

Figure 3.1: Tracings of force to removal aligner from testing models

Chapter 4: Discussion

Over the past decade, the demand for an esthetic alternative to traditional fixed orthodontic brackets has witnessed a remarkable surge. Notably, there has been an increasing trend of adult patients seeking orthodontic treatments (Rossini, 2015). However, clear aligner therapy comes with known mechanical limitations, and conventional fixed braces might not be the most aesthetically pleasing option. Therefore, a system that combines the benefits of both options would be immensely advantageous for both clinicians and patients.

This theoretical novel esthetic orthodontic ceramic bracket system offers the unique advantage of correcting major rotations (1st order) and mesial-distal tips (2nd order) efficiently within three to six months, which is known to be the advantage of conventional fixed orthodontics. Additionally, during this initial orthodontic phase, predictable leveling of dental arches can be achieved, a task that clear aligner therapy alone struggles to accomplish efficiently.

Once these major movements are corrected, selected brackets are removed, and dental arches can be scanned for clear aligner therapy. This eliminates the challenging aspect of finishing with a continuous archwire, which adheres to Newton's 3rd Law: Action & Reaction, stating that every action (force) in nature has an equal and opposite reaction. Therefore, it is known that detailing and finishing is the most difficult phase of conventional fixed orthodontics. Clear aligners however have less of a continuous archwire effect and can be programmed to hold, not move, some teeth while moving others which allows for increased finishing control. Theoretically, this system overcomes the limitations of both conventional fixed and aligner theory mechanics while maximizing the benefits of each, resulting in an exceptionally efficient orthodontic system.

The demand for diverse orthodontic treatment options remains exceedingly high, motivating our initial investigation. A survey conducted on over 250 adult orthodontic patients representing a diverse demographic, it was evident that many individuals found conventional fixed orthodontic appliances unattractive. Moreover, a significant number of respondents expressed their willingness to pay more for an esthetic alternative or option (Alansari, 2019; Rosvall, 2009).

Recent studies have also revealed a strong preference for aesthetic options like lingual braces and clear aligners among both adult and young patients (Alansari, 2020). With this background, our investigation sought to explore the feasibility of a theoretically designed orthodontic system that can seamlessly integrate with both conventional fixed and aligner therapy mechanics. We aimed to assess whether this novel trapezoidal orthodontic bracket system can effectively accommodate a thermoformed aligner material while providing a level of retentive force comparable to that of traditional aligners.

4.1 Clinical Relevance and Theoretical Implications

Our primary objective was to investigate the compatibility of a novel orthodontic trapezoidal bracket slot geometry with thermoformed aligner material. The aim was to select a suitable slot geometry from the investigation for future testing of the innovative orthodontic system, designed to serve both conventional fixed and clear aligner mechanics.

Based on the results obtained, we found that the novel orthodontic slot geometry effectively engages with thermoformed plastic aligner material. Notably, intriguing variations were observed among the different slot configurations studied.

As indicated by the results, the majority of configurations demonstrated a mean retentive force ranging from 3-4 lbs for aligner removal from the model. However, there were outliers in the no attachment and 0.018” x 0.060” group, exhibiting a mean retentive force above 4 lbs. To put this into context, a study comparing the retention force of aligner removal with various attachments found that two 2 mm horizontal bevel retention attachments on two bicuspids resulted in a retentive force of 30 N or 6.7 lbs (Dasy, 2015). Our control group, the 2 mm horizontal bevel attachment group which was tested in the above study, displayed similar mean retentive force values to those reported in that study.

After conducting statistical analysis, our goal was to achieve a mean retentive force close to that of our control group, the 2 mm horizontal bevel retention attachment, which represents the current industry standard for aligner retention. The 0.014” x 0.060” slot geometry group, upon comparison, showed statistically insignificant retentive force to remove the aligner when compared to the 2mm horizontal bevel retention attachment group, indicated similar retentive forces and mechanics.

One thing our investigation confirmed from prior research is the trim line of the aligner matters. The no attachment group with the trim line 1mm above the gingival margin should statistically significance among all groups. (Cowley, 2012)

A notable trend observed in the statistics is that the 0.060" top of slot group, for both 0.014" and 0.018" base brackets, showed a statistically significant difference compared to the 0.040" and 0.050" top of slot groups. This finding suggests that the increased divergence of the bracket walls in the 0.060" top of slot group allows the thermoformed plastic to flow more effectively into the slot. On the other hand, the 040" and 050" top of slot groups might not provide sufficient divergence for the thermoformed aligner material to adequately engage with the bracket slot.

In considering future investigations into this novel orthodontic system, the 0.014" group can prove advantageous in certain treatment objectives, particularly in extraction cases. The provisional patent demonstrates a theoretical clinical application of a two-wire binding protocol for extraction treatment. With the 0.014" base, a smaller base wire like 0.014" or 0.016" stainless steel can be used, overlaid with an 0.018" stainless steel wire to facilitate proper sliding. This configuration results in a wire height of 0.032" – 0.034" that ties into the bracket effectively.

However, if an 0.018" base were to be used instead, a larger base wire like 0.018" or 0.020" stainless steel, overlaid with an 0.018" stainless steel wire for sliding, would create a height of 0.036 – 0.038". This would pose difficulties for clinicians to tie the wire at the bracket slot height, which is only 0.030".

4.2 Hypothesis Evaluation

Our aim in this study was to evaluate the following research questions:

1. Does no clear aligner attachment differ in the amount of force required to remove the clear aligner compared to different trapezoidal orthodontic slot dimensions?

- Null Hypothesis: H0: There is no difference in the amount of retention of a clear aligner between no clear aligner attachment and the different novel orthodontic trapezoidal slot geometries.

The amount of retentive force measurements from mechanical testing indicated that the Null Hypothesis for the first research question was rejected for all seven groups. Statistically significant force levels in pounds (lbs) were seen in the 0.014" vs. No attachment, 0.018" vs. no attachment, and 2 mm retentive attachment vs. no attachment groups.

2. Does a 2mm horizontal bevel retention clear aligner attachment differ in the amount of force required to remove the clear aligner compared to different orthodontic slot dimensions?

- Null Hypothesis: H0: There is no difference in the amount of retention of a clear aligner between the 2 mm horizontal bevel retention clear aligner attachment and the different novel orthodontic trapezoidal slot geometries.

The Null Hypothesis was partially rejected for the second research question as the 2 mm attachment vs. 0.014” x 0.060”, 2 mm attachment vs. 0.018” x 0.040”, and 2 mm attachment vs. 0.018 x 0.050” groups were not clinically significant. All other groups were clinically significant. This was a significant research question to test in order to finalize final bracket geometry selection for future testing.

3. Does the geometry of different orthodontic slot configurations at the top of the slot affect amount of force required to remove a clear aligner?

- Null Hypothesis: H0: There is no difference between novel trapezoidal orthodontic slot geometries and aligner retention.

The Null Hypothesis was partially rejected for the third research as both the 0.014” and 0.018” base groups when comparing the top of the slot group, 0.040” vs. 0.050”, both displayed statistical insignificances. For both 0.014” and 0.018” base groups when comparing the top of slot groups 0.040” vs. 0.060” and 0.050” vs. 0.060”, all displayed statistical significance.

4. Does the geometry of different orthodontic slot configurations at the base of the slot affect amount of force required to remove a clear aligner?

- Null Hypothesis: H0: There is no difference between novel trapezoidal orthodontic slot geometries and aligner retention.

The Null Hypothesis was rejected for the fourth research question as there was statistical significance displays in all groups tested. The 0.014” and 0.018” base of slot groups in 0.040”, 0.050”, and 0.060” top of slot groups all displayed statically significance.

4.3 Limitations and Suggestions for Future Research

As an *in vitro* investigations, a common limitation is related to the methodology of the study. These force readings were created off aligners that were applied to replicated 3D printed resin dental models. It must be assumed that all of our measurements have a certain level of approximation. The system and study set out to investigate the possibly of using this novel system on a biological system which has far more factors that one can’t duplicated in an *in vitro* lab bench study.

A second limitation of our study was limited to a single direction of force to remove the aligner from the plastic resin model, which does not account for the complex force system and reciprocal forces generated when removing an aligner. Future, the study design did not account for biological effects of the intraoral environment such as occlusal forces, effect of saliva, location of which individual removed the aligner, and the possible repeated loading of the aligners as they are worn 20 + hours a day for one to two weeks at a time in talking, chewing, habits, etc.

A third limitation of our study is related to the thermoforming process. Despite stringent study protocol, the following of manufacturer guidelines and regulations, differences align quality from thermoforming process was noted. This is hypothesis to be due to fluctuation in temperature of heating element of thermoforming machine as multiple aligners were made in a consecutive row. Due to the non-uniform heat applied to the aligners, impacts of aligner thickness and force delivery of the teeth can be of significance.

Lastly, investigator's error should not be overlooked. Primary investigator (KG) conducted all phases of this investigation, from digital scanning of typodont model, fabrication of testing model, thermoforming and trimming of aligners, and carrying out Instron treatment simulation cycles.

Our study specifically aimed to examine if plastic would flow into and create retention in the alternative trapezoidal slot form. Secondly, if it was able to flow into the trapezoidal slot, how would the retentive force compared to current market attachments and no attachments. The *in-vitro* simulations of a second premolar retention, a common tooth for retention of aligners, aimed to compare the different slot forms. Treatment efficiency is equally important to patients and clinicians, therefore this investigation is a first step in creating a novel orthodontic system that can be used for both aligners and convention fixed braces. An efficient orthodontic system that can be used for both convention fixed braces for harder rotation movements and finishing in aligners could decrease the need for lengthy and unwanted aligner treatment plans and revisions.

Future research is necessary to evaluate the ability of the trapezoidal slot to torque teeth, third order movement, and the ability to sliding and bind in space closure mechanics. Lastly, we believe our experiment can be used as a guide for a future *in vivo* study with a split-mouth design to access the effect of novel system compared to conventional attachment design.

Chapter 5: Conclusions

The following conclusions can be drawn from the analysis of the results in our study:

1. The bracket slot configuration that most closely resembles the current 2mm horizontal bevel aligner retention attachment is 0.014” x 0.060”. As seen in the t-test, there was statistical insignificance on amount of force required to remove the aligner from the model. The mean force was very similar at 3.50 +/- 0.73 lbs for 0.014” x 0.060” and 3.60 +/- 0.69 lbs for 2mm horizontal bevel retention attachment. One of the theoretical applications in the provisional patent for this novel bracket is the ability to use a two wire system to bind posterior teeth in extraction cases for anchorage. An 0.018” base of slot would require much wider initial wire, 0.020” stainless steel or nickel-titanium, which would create a bulky tie in for the posterior. In the 0.014” base of slot, a base wire of 0.014” stainless steel or nickel-titanium could be used with a conventional sliding wire of 0.018” stainless on top to allow adequate sliding. This would create a height of the two wires at 0.032” in the 0.014” base system where as in the 0.018” system with a 2 wire system of 0.018” and 0.018” would create a height of 0.036”. Further investigation needs to be completed on sliding mechanics of selected bracket slot configuration of 0.014” x 0.060”.

2. The top of slot dimension of 0.060” is statistically significant in both the 0.014” and 0.018” base of slot systems. This is mostly likely due to the increase in divergence natural of the bracket walls that allow easier flow of thermoformed plastic into the trapezoidal slot.

3. As seen in other studies, location of trim line does matter in aligner retention. The control of no attachment with trim line 1mm above gingival margin shows statistical significance among all groups tested.

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Curriculum Vitae

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Education

University of Nevada: Las Vegas (UNLV); Las Vegas, NV 05/2017
Doctor of Dental Medicine: D.M.D.

- GPA: 3.72; Class Rank 5/74
- Graduated *Cum Laude*
- Member of *Omicron Kappa Upsilon* Honorary Dental Society
- Awarded Delta Dental Student Leadership Award, AAMOS Award
- Received 2016-17 Las Vegas AAID Maxicourse Student Scholarship
- Member of UNLV School of Dental Medicine Honor's Clinic

Western New England University; Springfield, MA 05/2012
Bachelor of Science: B.S. Biology

- Major GPA: 4.0; Cumulative GPA: 3.97
- Graduated *Summa Cum Laude*
- Dual Minors in Chemistry & Forensic Biology
- Member of *Alpha Lambda Delta* First Year Honors Society, Mortar Board Leadership Honors Society, *Chi Alpha Sigma* Athletic Honors Society
- Awarded University Biology Achievement Award
- Elected Captain of NCAA Men's Ice Hockey Team - Junior & Senior Year
- Dean's & President's List all four years

University of Nevada: Las Vegas (UNLV); Las Vegas, NV 07/2020- Present
Advanced Education Program in Orthodontic and Dentofacial Orthopedics
- Candidate for Certificate in Orthodontics- April 2024
- Candidate for Master of Science in Oral Biology- April 2024

Work History

Lead General Dentist / NuYu Dental 05/2020- 09/2021
Round Rock, TX
- Performed a wide range of restorative, cosmetic, and implant procedures
- Managed and motivated staff, set practice metrics, increased production of staff and practice

Associate General Dentist / The Hills Dental Spa 07/2018-04/2020
Austin, TX

- Performed a wide range of restorative, cosmetic, and implant procedures that include CEREC CAD/CAM crowns & onlays, cosmetic bonding, veneers, and clear aligner therapy
- Completed over Thirty (30) cases of Invisalign®

Associate General Dentist / MOD Squad Dental 06/2017-07/2018
San Diego, CA

- Performed a wide range of restorative, cosmetic, and endodontic procedures that include Itero scanning for crowns & onlays, cosmetic bonding & veneers, and rotary endodontic therapy (WaveOne, Vortex Blue, ProTaper Gold)

Associate General Dentist / Dr. Ruben Romero, DDS 06/2017-07/2018
San Diego, CA

- Performed the same responsibilities as MOD Squad Dental

Associate General Dentist / Dr. Yolonda Lorett, LLC 11/2017-07/2018
San Diego, CA

- Performed the same responsibilities as MOD Squad Dental

Research

Grahl K, Rich B, Ingel AP (2016) A Guided Surgical Technique for the Use of Small Diameter Implants in the Anterior Mandible: Report of a Case. Oral health case Rep 2: 123. doi:10.4172/2471-8726.1000123

- Oral Presenter (Feb. 2016), 2-Day Mini Dental Implant Course hosted by Shatkin F.I.R.S.T. Las Vegas, NV
- Poster Presentation (Feb. 2016) Dean's Symposium & 14th Annual Research Day. UNLV SDM. Las Vegas, NV
- Poster Presentation (Aug. 2016) 2016 ICOI Summer Symposium. San Diego, CA
- Poster Presentation (Oct. 2016) 2016 AAID Annual Meeting. New Orleans, LA
- Publication: Oral Health Case Reports September 2016

Grahl K, Kingsley K. (2015) Role of race/ethnicity and melatonin expression among healthy adults

- Poster Presentation (Mar. 2015), International Association of Dental Research (IADR). Abstract #2110496. Boston, MA
- Poster Presentation (Feb. 2015). Dean's Symposium & 13th Annual Research Day. UNLV SDM. Las Vegas, NV