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ABSTRACT

Title of dissertation: Coated Rectangular Composite Archwires: A Comparison of Self-Ligating and Conventional Bracket Systems During Sliding Mechanics

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The purpose of this study was to analyze the resistance to sliding of coated rectangular fiber reinforced composite archwires using various brackets systems and second-order bracket angulations. Resistance to sliding was investigated for eight bracket systems: six self-ligating brackets (four passive and two passive-active) and two conventional brackets. A rectangular fiber reinforced composite archwire of 0.019 x 0.025-in dimension from Biomers® SimpliClear was drawn through a three-bracket model system at ten millimeters per minute for 2.5 millimeters. For each bracket, the resistance to sliding was measured at four bracket angulations (0°, 2.5°, 5°, and 10°) in a dry state at room temperature. The fiber reinforced composite archwire produced the lowest sliding resistance with the passive self-ligating bracket system (Damon DQ) at each bracket angulation tested. Overall, self-ligating bracket systems generated lower sliding resistance than conventionally ligated systems, and one passive/active self-ligating bracket system (In-Ovation-R). There was a significant increase in resistance to sliding as bracket angulation increased for all bracket systems tested. Microscopic analysis revealed increased perforation of the archwire coating material as bracket angulations were increased. Our findings show that the rectangular fiber reinforced composite archwire may be acceptable for sliding mechanics during the intermediate stages of orthodontic tooth movement, however more long-term studies are needed.

COATED RECTANGULAR COMPOSITE ARCHWIRES: A COMPARISON OF SELF
-LIGATING AND CONVENTIONAL BRACKET SYSTEMS DURING SLIDING
MECHANICS

by
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I. INTRODUCTION

With the growing number of adult patients seeking orthodontic treatment, the demand for esthetic orthodontic appliances has steadily increased. Societal demand for increased esthetics has fueled many new developments in orthodontic appliances. Minimally visible orthodontic appliances, such as clear aligner therapy and lingual braces, have shown considerable popularity among orthodontic patients. As more adults continue to seek orthodontic treatment, the demand for esthetic orthodontic appliances that provide efficient tooth movement also increases. Tooth colored appliances, such as ceramics and polymers, are beginning to replace traditional metal brackets and metal archwires. Recently, clear composite archwires have been developed for use during the initial and intermediate stages of orthodontic treatment. During the initial stages of orthodontic tooth movement small and flexible archwires are used to level and align mal-positioned teeth.¹ Larger rectangular archwires are often used during intermediate stages for rotation control, expression of torque, and space closure.² Rectangular archwires are particularly important during space closure because they allow greater control of the dental arch form during sliding mechanics. Given the unique properties of composite archwire materials these archwires may provide improvements to the existing esthetic orthodontic appliances. However, further study is needed to examine the performance of these archwires given the limited research in this field.

II. LITERATURE REVIEW

Background

Until recently, archwires consisted of four non-esthetic alloys: stainless steel, cobalt-chromium, nickel titanium (NiTi), and beta-titanium.³ There are currently two esthetic archwire options available for orthodontic use, coated metal alloys and composite polymers. Metal archwires have been coated with tooth-colored polymers to conceal the visibility of the underlying alloys.⁴ Despite their esthetic enhancements, coated metal archwires have a number of limitations, such as lack translucency, wear of the outer coating, and limited ability to match a patient's natural tooth shade.⁵ Due to their translucent and transparent properties, composite polymers offer an esthetic alternative to coated metal archwires. Despite their esthetic advantages first generation polymer archwires had drawbacks that limited their clinical use.

Prototype polymer materials lacked sufficient rigidity and strength to function as adequate substitutes for metal alloys. Poor stress relaxation and low hardness led to exaggerated deformation and increased frictional resistance of the polymer archwires.⁶ Reinforcement of composite polymers with continuous glass fibers provided increased rigidity and strength to these prototypes and resulted in the development of a new material, fiber reinforced composites (FRC).⁷ Fiber reinforcement of composites have been discussed in the dental literature since the early 1960s, beginning with polymethyl-methacrylate denture resins.⁸ However, fiber reinforced composite (FRC) archwire were not introduced to orthodontics until the 1990s when Goldberg et al.,⁷ used S-glass fibers and thermosetting Bisphenol-A-diglycidyl methacrylate (bisGMA) to produce prototype

archwires. In 1999, Kusy et al.⁹ patented a method called photo-pultrusion, which improved production of FRC wire.

In 2008, Biomers®, a medical device company based in Singapore, received FDA approval for clinical use of a proprietary fiber reinforced composite archwire system, which is currently marketed as the first completely clear archwire system for the treatment of mild to complex orthodontic cases. Biomers® has recently released its first FRC rectangular archwire for use during the latter stages of orthodontic treatment, such as space closure. Currently, no studies have evaluated the frictional characteristics of these rectangular composite archwires.

Properties of Fiber Reinforced Composite Archwires

FRC archwires offer some advantages over existing metal archwires due to the manufacturer's ability to vary stiffness without changing archwire dimension (variable modulus), and the ability of the clinician to bond composite attachments directly to the wire due to the archwires composite composition. Additionally, FRC avoids some of the drawbacks present in metal alloys, such as, poor esthetics, radiopacity, and nickel allergy.¹⁰ Composite archwires reinforced with S2 glass fibers show minimal (1%) loss of tensile strength in moist environments, which suggests that they would be stable in oral environments.¹¹ FRC wires are extremely strong and rigid in tension, but weak in shear and torsion properties.⁷ Because of their brittle nature, FRC archwires are susceptible to breakage in the mouth from abrasive wear, particularly at large points of flexure.⁶ Early studies evaluating the frictional characteristics of prototype FRC wires during simulated tooth movements (sliding mechanics) found increased wear and fracture

of FRC wires at elevated bracket-archwire angulations.¹² These prototype FRC archwires were deemed unacceptable for clinical use because of the risk of releasing glass particles within the oral cavity. To prevent the release of glass fiber particles, a polymer coating material, Parylene C (poly chloro-p-xylylene), used in other medical devices such as catheters, was applied to prototype FRC wires. Despite increasing the kinetic coefficient of friction, these archwire coatings eliminated the release of glass fibers from FRC wires making them acceptable for clinical use.¹¹

Esthetic Orthodontic Archwire Materials

As previously stated, there are presently two options for esthetic orthodontic archwire materials: coated metal alloys and fiber-reinforced composites. Tooth colored coating materials for metallic alloys, particularly nickel titanium, come in two varieties: synthetic fluorine-containing resin (plastic), and epoxy resin (polytetrafluoroethylene, Teflon®).¹³ Studies have reported poor durability of coated NiTi archwires related to color change and coating splits during usage in the oral environment that exposes the underlying metal alloy.^{14,15} When the frictional behavior of plastic-coated NiTi archwire was compared with non-coated NiTi archwire from the same manufacturer, plastic coatings were found to significantly decrease frictional interactions between archwires and brackets.¹⁶ Unfortunately, coated NiTi archwires are routinely damaged from the forces of mastication and enzymatic activity in the oral cavity, resulting in wear and peeling of the esthetic coating within three weeks.¹⁷

Previously, FRC wires were only experimental prototypes not available for commercial use. FRC wires can now be fabricated using a pultrusion method, whereby glass fibers are pulled through a resin and wetted monomer followed by curing of the

resin by light or heat and pressure.⁸ Wires can be further shaped into circular or rectangular cross sections by a partial curing process, known as Beta-staging.⁸ Using the photo-pultrusion method, unidirectional fiber reinforced polymer (UFRP) archwires of thin circular cross-sections have been produced that weigh seventy-five percent less than stainless steel wires of similar dimension and possessed similar strength.⁹ By altering the orientation and percentage of fiber within the composite wires, it's possible to customize FRC wire properties to the desired specifications. Short glass fibers result in low stiffness, or modulus of elasticity, while long and continuous fibers in parallel array produce a greater stiffness and larger elastic recovery (springback) for increased orthodontic force delivery.^{7,8} Studies of round FRC prototypes suggest that these archwires may function well during the initial leveling/aligning phase of orthodontic treatment where minimal exposure to the frictional forces of sliding mechanics are present.¹²

BioMers ® SimpliClear is the first commercially available and FDA- approved FRC archwire system. This proprietary composite archwire is reinforced with continuous glass fibers and coated with a protective outer covering to prevent the potential release of glass particles within the oral cavity. BioMers® round composite archwires are found to have similar mechanical characteristics to nickel titanium (NiTi) wires of comparable dimensions.¹⁹ In an unpublished study, BioMers ® round composite archwires generated lower friction than uncoated nickel titanium archwires using an aligned bracket system model.²⁰

In a recent unpublished study, Gallagher et al.²¹ evaluated the initial frictional resistance to sliding generated by various combinations of ceramic brackets and esthetic

orthodontic archwires, using a non-aligned experimental bracket model. In this study, two types of esthetic bracket systems, self-ligating and conventional twin, were evaluated with five different archwire materials of 0.018-in round dimension. This study found that Teflon ® coated NiTi archwire demonstrated the lowest initial resistance to sliding; and BioMers ® FRC archwire produced similar frictional values as rhodium coated NiTi wires; which, in turn, produced significantly less friction than stainless steel and uncoated NiTi archwires. Ceramic self-ligating brackets also produced lower frictional resistances than ceramic conventional brackets. Stainless steel self-ligating brackets were not tested. This study supported the findings of Kusy et al.¹² which found that FRC archwires produced higher friction than stainless steel, but lower friction than uncoated nickel titanium or beta-titanium archwires of similar archwire dimension.

Importance of Friction in Orthodontics

Nikolai et al.²² evaluated the frictional forces generated in an experimental model simulating canine-retraction on a continuous arch wire. Regression analyses indicated that with standard edgewise brackets, the frictional resistance increases with: bracket width, archwire dimension, bracket/wire angulation, ligature force, and cross-sectional shape (rectangular archwire). Small changes in the inter-bracket distance had minimal impact on frictional resistance, thus changes in inter-bracket distance during canine retraction were unlikely to influence frictional results. With small non-binding bracket angulations, bracket width and ligature force were found to dominate frictional resistance. As bracket/wire angulations increase, the influence of bracket width and ligation force diminishes, while the influence of wire dimension, wire shape, and wire stiffness (modulus) became more influential. These results suggest that tooth movement

will occur with greater ease when ligation force and archwire-bracket binding are minimized.

Resistance to Sliding in Orthodontics

During orthodontic tooth movement, frictional forces resisting tooth movement are generated at the interface of the archwire and bracket slot. Two types of friction exist: static friction and kinetic friction. Static friction is the force required to initiate movement, while kinetic friction is the force required to maintain motion. Kinetic friction is usually less than static friction. Kinetic friction is irrelevant in clinical orthodontics because tooth movement occurs so slowly that continuous motion rarely occurs.²³ It has been proposed that as much as 50% of the force applied to slide a tooth along an archwire is used to overcome sliding resistance.²⁴ Classical literature regarding the resistance to tooth movement has mainly focused on friction, however, friction is only one aspect of the resistance as a bracket slides along an archwire.

Kusy and Whitley²⁵ divided resistance to sliding (RS) into three components: (1) friction (FR), the resistive force generated by surface roughness and archwire ligation; (2) binding (BI), the resistive force created when a tooth tips, thereby creating contact between the archwire and the edges of bracket slot; and (3) notching (NO), the resistive force created at extreme archwire-bracket angulations that results in archwire deformation (notching). Friction is constant when the archwire lacks contact with the edges of the bracket slot, this is called *passive configuration*.²⁶ The angulation necessary to produce contact between the archwire and edges of the bracket slot is called the critical contact angulation (θ^C).²⁶ When the archwire-bracket angulation exceeds the θ^C , binding occurs, this referred to as *active configuration*.²⁶ Because tooth movement requires bone

remodeling, teeth do not move in a smooth continuous motion but rather in a sequence of short steps.²² Force applied at the level of the bracket tips the tooth until the archwire contacts the edges of the bracket slot, producing binding. At severe bracket angulations the archwire can be notched or permanently deformed as the bracket edges gouge the archwire surface, thereby preventing tooth movement until elastic wire deformation, bone remodeling, or vibrations from mastication permit movement beyond this notch.²³ After a tooth tips and contact is created between the archwire and edges of the bracket slot. Binding and notching create a counter-rotational force in the opposite direction of the applied force that serves to upright the root of the tooth. Once the tooth is upright, this process repeats itself. Articulo and Kusy²⁷ found binding and notching to be the primary components of resistance to tooth movement in clinical orthodontics. O'Reilly et al.²⁸ evaluated the resistance to sliding of an oscillating bracket system and concluded that intermittent movement between the bracket and archwire during sliding mechanics demonstrate a binding and releasing phenomenon.

In clinical orthodontics, the resistance to sliding can be a positive attribute used to prevent tooth movement in circumstances that require anchorage for tooth control. Alternatively, resistance to sliding can be a negative attribute that prevents desired tooth movement in circumstances requiring space closure or space opening. As the resistance to sliding increases, the force required to achieve desired tooth movement also increases. Because light forces are more favorable to initiate and maintain tooth movement, reduce pain, and maintain the position of anchorage teeth, it's beneficial to reduce the resistance to sliding in clinical orthodontics during sliding mechanics.²⁹

Effect of the Bracket Ligation Method on Sliding Resistance

The reduction of bracket ligation forces can help reduce the frictional component of sliding resistance.³⁰ The literature describes three methods for ligating an archwire within a bracket slot: stainless steel ligature wires, elastomeric ligatures, and self-ligating (SL) brackets with passive or active clips.³¹ There are three types of self-ligating brackets: active, passive, and passive-active. Active SL brackets possess a clip that engages the archwire with greater force as archwire dimension increases.³¹ Passive SL brackets have a clip that retains the archwire in the bracket slot without applying ligation force as archwire size increases.³¹ Passive-active brackets have clips that do not engage the archwire until the wire exceeds a pre-set size. Unlike elastomeric or stainless steel ligation, self-ligating brackets apply a constant and more reproducible ligation force. Stainless steel ligatures have been found to deliver more variability in ligation force compared to elastomeric ligatures.³² Generally, loosely tied stainless steel ligatures are thought to produce lower frictional resistance than standard elastomeric ligatures, however the convenience and speed of applying elastic ligatures have ensured their popularity in the clinical setting.³² Studies have shown that the mean variability in force for stainless steel ligation was three times greater when compared to elastomeric ligation.³² It should be noted that elastomeric ligature forces decrease due to material fatigue, which can significantly reduce their ligation force over time.

SL brackets are not new to orthodontics. They were first introduced in the 1930s in an attempt to enhance clinical efficiency by reducing ligation forces.³³ There has been a recent resurgence in studies of SL brackets to evaluate manufacturer's claims of decreased treatment time compared to conventionally ligated brackets.³⁴ Controversy

ensues as some studies report reduced friction with SL brackets,³⁵ while other studies have reported similar frictional forces for SL and conventionally ligated brackets.³⁶

Overall, there seems to be a consensus that self-ligating brackets generate lower sliding resistance compared to conventional brackets, due to the decreased ligation forces exerted by self-ligating brackets on the archwire.^{37,38} Active and passive self-ligating brackets have been found to produce lower sliding resistance compared to conventionally ligated brackets, particularly with small round wires dimensions.³⁹ Active self-ligating brackets were shown to produce greater sliding resistance compared to passive self-ligating brackets when larger rectangular archwires were utilized for sliding mechanics.³⁹

Thornstenson and Kusy³¹ compared the resistance to sliding between conventional and self-ligating stainless steel brackets, using 0.018 x 0.025-in stainless steel archwire, at various bracket angulations. Their study found that self-ligating and conventional brackets produced similar sliding resistance when ligated with the same stainless steel ligature force. Passive self-ligating brackets produced sliding resistance that was lower than conventionally ligated brackets. Active self-ligating brackets produced binding forces that were similar to conventional brackets tied with loosely tied stainless steel ligatures. Thus, the difference in sliding resistance between these two bracket systems, conventional and self-ligating, is largely related to the reduction in ligation force found in some self-ligating brackets. Additionally, conventionally ligated brackets have a reduced critical contact angle compared to self-ligating brackets because the ligatures (whether stainless steel or elastomeric) tend to increase the effective bracket width. The authors concluded that self-ligating brackets provide ligation forces that are reduced and more reproducible compared to conventionally ligated brackets.

Despite their advantage of reduced sliding resistance, it has been clinically observed that self-ligating brackets with larger bracket slot dimension have a difficult time achieving ideal tooth alignment compared with conventional brackets.⁴⁰ The increased bracket slot size of some passive self-ligating brackets may reduce the resistance to sliding at the expense of controlling root and crown position.^{41,42,43}

A systematic review of the literature by Ehsani et al.⁴⁴ found that most in-vitro studies incorrectly interpret friction as the resistance to sliding. Most studies agree that in the absence of extreme bracket rotations, self-ligating brackets produce lower frictional forces when paired with small round archwires.³⁹ Most studies also agree that the resistance to sliding increases for both self-ligating and conventionally ligated bracket systems as archwire size increases.⁴⁴ In the presence of bracket angulation, rectangular archwires produced lower sliding resistance with self-ligating brackets compared to conventional brackets. This may be related to a difference in ligation forces and bracket dimension.⁴⁵ It has been observed that stainless steel brackets and archwires consistently produce lower frictional forces in passive bracket configurations when compared with ceramic and polycarbonate conventional brackets.^{42,43} This reduction in friction is most likely related to the increased roughness and porosity of the ceramic and polycarbonate materials.³⁷

Practitioners must weigh the advantages and disadvantages of any bracket system in order to determine which is best for them, as no ideal bracket system exists. In a recent review article, the core assets of self-ligation were summarized as follows: secure, full archwire engagement; lower resistance to sliding between bracket and archwire; faster placement and archwire removal; and less need for chair-side assistance.⁶³ Furthermore,

all of the randomized controlled studies on self-ligating bracket systems show no difference in treatment time, number of visits, or better tooth alignment compared to conventional bracket systems.⁶³ Despite the differences in sliding resistance, the overall treatment time of conventional and self-ligating bracket systems may not differ when applied to a general mix of orthodontic malocclusions. Thus practitioners must choose which bracket system is adequate enough based on biomechanical needs and patient considerations.

Effect of Bracket Angulation on Sliding Resistance

After examining the resistance to sliding of self-ligating brackets with active and passive slides, using 0.018 x 0.025-in stainless steel archwire, at various (second-order) bracket angulations, Thornstenson and Kusy³¹ found that the critical contact angulation for self-ligating brackets ranged from three to five degrees. Below this critical contact angulation, brackets with passive slides exhibited negligible frictional forces, while brackets with active clips produced forces up to 50cN (50g).³¹ Once the critical contact angle(θ_C) has been exceeded, both brackets have increased binding forces independent of the bracket design. Resistance to sliding equals the summation of friction and binding forces ($RS = FR + BI$). Brackets with higher friction forces or lower critical contact angles tend to produce greater amounts of sliding resistance. This study found that the critical contact angle for conventionally ligated brackets was smaller (2.9 degrees) compared to self-ligating bracket systems (3.8 degrees), which tended to have narrower bracket widths.

Articolo and Kusy²⁷ studied the influence of bracket angulation on the resistance to sliding using rectangular 0.021 x 0.025-in archwires of various materials. They found that binding forces were initiated at three degrees of bracket angulation (the critical contact angle), quickly dominated the resistance to sliding, and increased as angulation increased. At seven degrees of bracket angulation, binding represented 80% of the resistance to sliding, and 99% at thirteen degrees.²⁷ In the active configuration, the relative rankings of archwire-bracket materials was transposed: pairs of stainless steel brackets and stainless steel archwires produced a greater resistance to sliding, while flexible nickel titanium wires produced the least resistance to sliding. This study noted that binding and notching were the primary components of sliding resistance.

Effect of Archwire and Bracket Composition on Sliding Resistance

Archwire composition has changed over the years. In the late 1930s, orthodontic archwires were composed of gold, which was later replaced by stainless steel in the 1950s.⁴⁶ Today the four metal alloys used in orthodontic treatment (stainless steel, chromium-cobalt, nickel titanium, and beta titanium) have specific properties and attributes which can greatly influence the resistance to sliding. On the basis of their coefficients of friction, archwires can be ranked as follows: (least to most) stainless steel, chromium-cobalt, nickel-titanium, and beta-titanium. However, this order changes when bracket angulation is introduced, as previously discussed.

Stainless steel brackets and archwires have been accepted as the gold standard for sliding mechanics due to their reduced frictional resistances observed in laboratory studies.²⁷ However, when binding angulations are introduced, a transposition in archwire

effectiveness occurs, such that flexible (e.g. nickel titanium) wires produce lower sliding resistance compared to stiff (stainless steel) archwires.²⁷ These findings are supported by Creekmore's study⁵¹ which found that sliding resistance increased with increased archwire stiffness. Due to their elastic properties, flexible wires can negotiate the edges of the bracket slot more easily than stiff archwires.²⁷

Zufall, Kennedy and Kusy¹² found that uncoated FRC archwires have greater kinetic coefficients of friction compared than stainless steel archwires, but lower coefficients of friction than titanium archwires. These FRC prototypes were considered clinically unacceptable because the archwire fractured during binding interactions with angulated brackets thereby resulting in exposure of the underlying glass fibers. In a later study, it was determined that a coating material (Parlene-C, poly chloro-p-xylylene) was able eliminate the fracture and exposure of glass fibers from these prototype FRC archwires despite the increasing their kinetic coefficient of friction compared to uncoated FRC prototypes. However, binding coefficients were similar for both coated and uncoated FRC archwires.¹¹ The binding of these archwires was similar to titanium wires, which were lower than stainless steel.

Bracket composition and slot design can influence the sliding resistance between archwires and brackets. Stainless steel is commonly used to fabricate orthodontic brackets, however, the demand for more esthetic archwire materials has continually grown over the years. Tooth colored bracket materials come from two families; ceramics (including zirconia, and poly and monocrystalline alumina) and polymers (including polyurethane, polycarbonate, and polyoxymethylene). The advantages of ceramic materials are high strength in compression, color stability, and stain resistance. Despite

these advantages, several drawbacks remain for ceramic bracket materials, such as fracture during torsion and tipping movements, abrasion of the enamel surfaces on opposing teeth, and increased sliding resistance due to bracket roughness and porosity.^{54,55} Polymer brackets have fallen out of favor because of their decreased resistance to wear, insufficient hardness, staining, and inability to withstand the torque forces generated by rectangular wires.⁵⁶ However, reinforcement with ceramic fillers and stainless steel slot inserts have improved the properties and potential uses for polymer brackets.

Influence of Saliva on Resistance to Sliding

The inconsistent effects of saliva on sliding resistance have created controversy within the literature.³⁹ Kusy⁵² argued that an artificial saliva substitute does not replicate the properties of human saliva and should not be used to simulate the oral environment in studies evaluating sliding resistance. When human saliva is used for frictional studies, the results can be highly variable, due to the physical and chemical composition of the saliva being materials tested.⁵³ Moreover, because of the individual variability in saliva properties, enzymatic processes, and dietary habits, it is difficult to standardize the effects of salivary samples for research study.

III. PURPOSE OF PRESENT STUDY

The purpose of this study is to examine the effect of sliding Biomers® SimpliClear Torque A rectangular fiber reinforced composite archwire (0.019-in x 0.025-in dimension) in a three-bracket model system using 0.022 x 0.028” dimension edgewise brackets. This study evaluated eight bracket systems (six self-ligating and two conventional twin brackets) at various bracket angulations (0°, 2.5°, 5°, and 10°) mimicking tooth movement during sliding mechanics.

IV. HYPOTHESIS

Null Hypotheses

1. There is no significant difference in the resistance to sliding between self- ligating and conventional bracket systems tested at the same bracket angulations.
2. There is no significant difference in the resistance to sliding produced by different bracket angulations (0° , 2.5° , 5° , and 10°) within the three-bracket model system.
3. There is no interaction between bracket systems and bracket angulations as they relate to sliding resistance.

Research Hypotheses

1. The resistance to sliding for 0.019 x 0.025-in fiber reinforced composite archwires is lower with self-ligating brackets (Damon DQ and Damon Clear, In-Ovation-R, In-Ovation-C, RMO FLI SS, and RMO FLI CL) compared to conventionally ligated brackets (Clarity and Victory).
2. The resistance to sliding is expected to increase as bracket angulations increases (0° , 2.5° , 5° , and 10°).
3. An interaction is expected between bracket systems and bracket angulations with respect to sliding resistance.

V. MATERIALS AND METHODS

Procedures

Fiber reinforced rectangular composite archwire, Biomers ® SimpliClear Torque A system of 0.019 x 0.025” dimension, was evaluated using various bracket systems of 0.022 x 0.028” slot dimension. Eight bracket systems, six self-ligating and two conventional brackets, were evaluated in this study (See Table 1).

Bracket Type	Bracket Width*	Material & Ligation Method
Clarity ^a	0.130-in	Milled polycrystalline alumina, elastomeric ligation
Damon Clear ^b	0.137-in	Polycrystalline alumina, passive self-ligating bracket
Damon Q ^b	0.112-in	Stainless steel, passive self-ligating bracket
In-Ovation C ^c	0.134-in	Polycrystalline alumina, passive/active self-ligating bracket
In-Ovation R ^c	0.122-in	Stainless steel, passive/active self-ligating bracket
Victory Series TM ^a	0.124-in	Stainless steel, conventional bracket, elastomeric ligation
RMO FLI TM CL ^d	0.135-in	Ceramic, passive self-ligating bracket
RMO FLI TM SS ^d	0.114-in	Stainless steel, passive self-ligating bracket

*Cuspid bracket width

^a Registered trademark of 3M Unitek

^b Registered trademark of Ormco

^c Registered trademark of GAC

^d Registered trademark of Rocky Mountain Orthodontics

Table 1. Bracket Systems

Using a three-bracket model system to mimic orthodontic movement, the sliding resistance during simulated orthodontic tooth movement was analyzed at various bracket

angulations (0° , 2.5° , 5° , and 10°) for each bracket system. The experimental control in this study was the FRC archwire tested at zero degrees of bracket angulation for each bracket system. Tests were performed in the dry state at room temperature. The Biomers® manufacturer supplied FRC archwires in a sterile commercial packaging. Straight segments of FRC were cut from the ends of standard archwires into sixty-millimeter segments, using a distal end cutter.

Brackets were mounted using an acrylic block (3.0" length by 1.5" width by 0.25" thickness) and a mounting jig previously described in the literature (See Figure 1).⁵⁷

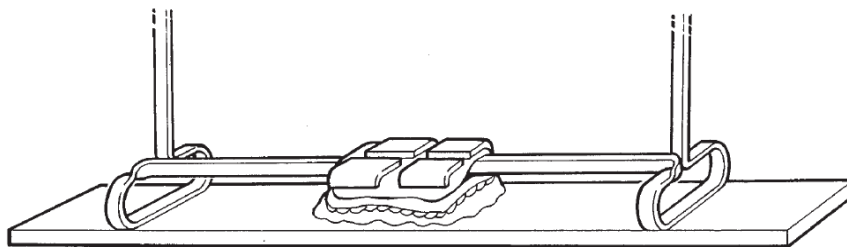


Figure 1. Diagram of 0.016" x 0.022" stainless steel mounting jig

Three brackets: a maxillary cuspid bracket, positioned centrally, and two adjacent maxillary bicuspid brackets, were positioned at an inter-bracket distance of 16 millimeters. Prior to bonding brackets to the acrylic block, the standardized mounting jig made out of 0.016 x 0.022" stainless steel archwire was constructed to reproducibly bond the brackets in their desired position and angulations. All brackets were positioned and bonded using the same mounting jigs for each bracket angulation tested to ensure consistent bracket positioning.

Each jig, one for each bracket angulation tested, was constructed so the largest dimension of the archwire (0.022") fully engaged the vertical dimension of the bracket slot. During bracket mounting, each conventional bracket was ligated to the 0.016 x 0.022" SS wire jig using an elastomeric ligature for the conventional brackets or the labial clip in the case of self-ligating brackets. The jig was constructed such that the ligated brackets were suspended roughly two millimeters from the acrylic block to eliminate the various tip, torque, and in-out prescriptions built into each bracket system (prescription) and allow adequate space for composite bonding material (See Figure 2).



Figure 2. Elimination of bracket prescription using 0.016"x 0.022" mounting jig

The acrylic block was marked with pencil at the corresponding bracket bonding sites and sandblasted in these regions to increase retention. Transbond™ Plus Self Etching Primer was applied with agitation to the bracket bonding sites for five seconds, and then dried with air for five seconds. Transbond™ Light Cure Adhesive (3M Unitek) was applied at the bracket bonding sites, and the bracket jig was seated over the corresponding bracket bonding sites with the archwire firmly seated at the base of the bracket slot. Brackets were light cured for 20 seconds using a standard curing light.

Brackets were mounted using an inter-bracket distance of 16mm from the center of the canine bracket to the center of each adjacent premolar bracket, in order to reduce the binding interactions at these adjacent brackets. An MTS Instron machine was used to draw FRC archwires through the mounted three-bracket model system at a rate of ten millimeters per minute for a total distance of 2.5mm (See Figure 3).

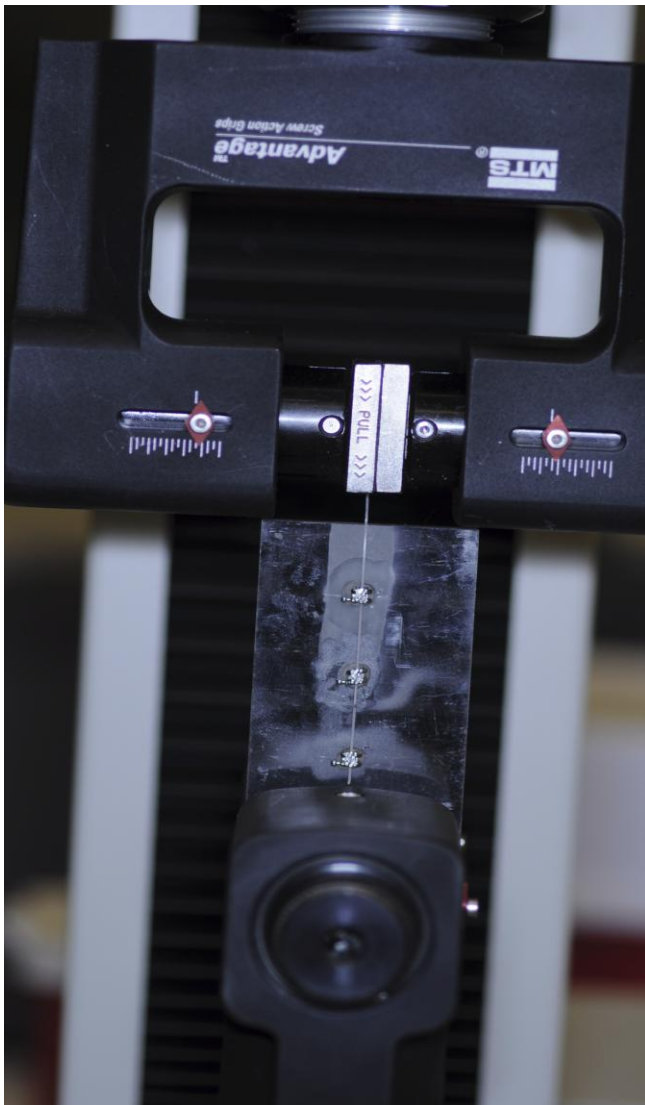


Figure 3. MTS Instron machine used in measuring resistance to sliding

The acrylic blocks with mounted brackets were attached to the lower member of the Instron machine, the straight segment of archwire was secured to the upper member, and the archwires were drawn vertically through the brackets. After each run, the archwire was removed from the mounting jig and repositioned to a fresh region on the FRC archwire. Drawing forces were measured and recorded using the TestWorks 4 computer program, previously calibrated and designed to test sliding resistance. The initial resistance to sliding was measured during the static phase of sliding mechanics for each test run.

At least seven archwires were tested for each bracket angulation (0°, 2.5°, 5°, 10°) for the eight bracket systems, for a total of 224 test runs. New brackets were used for each of the bracket angulations tested. Prior to each run, new elastomeric ligatures were applied and given one minute to adjust to the stretch over the conventional bracket wings prior to the starting of each experimental run. Self-ligating were secured to the archwire by closing the labial clips with finger pressure.

After testing each FRC archwire specimen, a microscopic analysis was performed under a stereomicroscope (Spencer Stereoscopic Microscope, American Optical Company, Buffalo, NY) to evaluate the integrity of the archwire coating materials and observe abrasive wear.

Statistical Analysis

Using an archwire sample size of seven, four levels of bracket angulation, and eight bracket systems, this study yielded an effect size of 0.40 for bracket angulations, 1.52 for bracket type, and 0.40 for the interaction between bracket angulations and bracket types. The power was 0.99 for angulations, 1.00 for bracket type, and 0.88 for

the interaction of angulation and bracket type with respect to sliding resistance (See Table 2).

Source	Effect Size	Observed Power
Bracket Angulation	0.40	1.00
Bracket Systems	1.52	1.00
Archwires X Brackets	0.40	0.98

Table 2: Effect Size and Observed Power for Results of Two-Way ANOVA

Data from this study was evaluated utilizing a factorial analysis of variance (ANOVA) to evaluate the differences for angulation, bracket type, and their interaction with respect to sliding resistance. If a significant difference was found, the main effects were then evaluated utilizing Tukey's Honestly Significant Difference (HSD) Test. Data was analyzed using IBM SPSS Statistics software (IBM Corp. Released 2012, Armonk NY). A p value ≤ 0.05 was considered significant.

VI. RESULTS

Results from the two-way analysis of variance (ANOVA) show the mean and standard deviations for sliding resistance for bracket systems and bracket angulations tested. Both bracket systems ($F=152.858$, $p \leq 0.0005$) and bracket angulations ($F=653.74$, $p \leq 0.0005$) had a significant difference with respect to sliding resistance. A significant interaction was observed in sliding resistance between bracket systems and bracket angulation with respect to sliding resistance ($F=8.21$, $p \leq 0.0005$, See Table 3).

		N	RS Mean	Std Dev	F	p
Brackets	Damon DQ	30	0.837 ^{a*}	0.860	152.858	.0005
	RMO FLI CL	31	1.622 ^b	1.530		
	RMO FLI SS	32	2.003 ^{bc}	1.623		
	Innovation-C	30	2.056 ^{bc}	1.989		
	Damon Clear	33	2.182 ^c	1.959		
	Innovation-R	30	3.914 ^d	2.162		
	Clarity	30	4.164 ^{de}	2.087		
	Victory	28	4.532 ^e	2.216		
Angulation	0 degrees	59	0.696 ^{a*}	0.754	653.74	.0005
	2.5 degrees	63	1.547 ^b	1.379		
	5 degrees	65	3.208 ^c	1.547		
	10 degrees	57	5.182 ^d	1.897		
Interaction	Bracket System X Angulation				8.21	.0005

Table 3. Two-Way ANOVA Results for Resistance to Sliding (RS) Measured in Newtons (N) for Bracket Systems and Bracket Angulation

The bracket system with the least resistance to sliding was Damon DQ (0.837 +/- 0.86 N), a passive self-ligating bracket system (See Table 4, Figure 4). The mean and standard deviations for sliding resistance for each bracket system at each bracket angulation tested is also shown in Table four.

Table 4. Mean Sliding Resistance and Standard Deviation for Each Bracket System at Each Bracket Angulation Tested

Bracket Systems	Angulation	RS Mean	Std. Deviation	N
Damon DQ	0 degrees	.09586	.045127	7
	2.5 degrees	.32237	.064111	8
	5 degrees	.71238	.064312	8
	10 degrees	2.30971	.125617	7
	Total	.83723	.859728	30
Damon Clear	0 degrees	.14175	.034321	8
	2.5 degrees	.54938	.081158	8
	5 degrees	3.17267	.717915	9
	10 degrees	4.74375	.621848	8
	Total	2.18282	1.959292	33
Innovation-R	0 degrees	1.54714	.153606	7
	2.5 degrees	2.78925	.489621	8
	5 degrees	4.25813	.673595	8
	10 degrees	7.17357	.987528	7
	Total	3.91413	2.161598	30
Innovation-C	0 degrees	.23563	.066852	8

	2.5 degrees	.75612	.138032	8
	5 degrees	2.41814	.175487	7
	10 degrees	5.26129	.502330	7
	Total	2.05633	1.988987	30
RMO FLI SS	0 degrees	.29343	.115181	7
	2.5 degrees	.57950	.184326	8
	5 degrees	2.97270	.757618	10
	10 degrees	3.95357	.757279	7
	Total	2.00288	1.622719	32
RMO FLI CL	0 degrees	.07163	.035104	8
	2.5 degrees	.71538	.519921	8
	5 degrees	2.12163	.232706	8
	10 degrees	3.85771	.928658	7
	Total	1.62171	1.530200	31
Clarity	0 degrees	1.39329	.132592	7
	2.5 degrees	3.66931	.957210	8
	5 degrees	5.07288	1.250863	8
	10 degrees	6.46214	1.262828	7
	Total	4.16418	2.087026	30
Victory	0 degrees	2.02429	.380051	7
	2.5 degrees	3.20357	.573497	7
	5 degrees	5.14043	.603842	7
	10 degrees	7.76014	.935069	7
	Total	4.53211	2.294801	28

Table 4. Mean Sliding Resistance and Standard Deviation for Each Bracket System at Each Bracket Angulation Tested

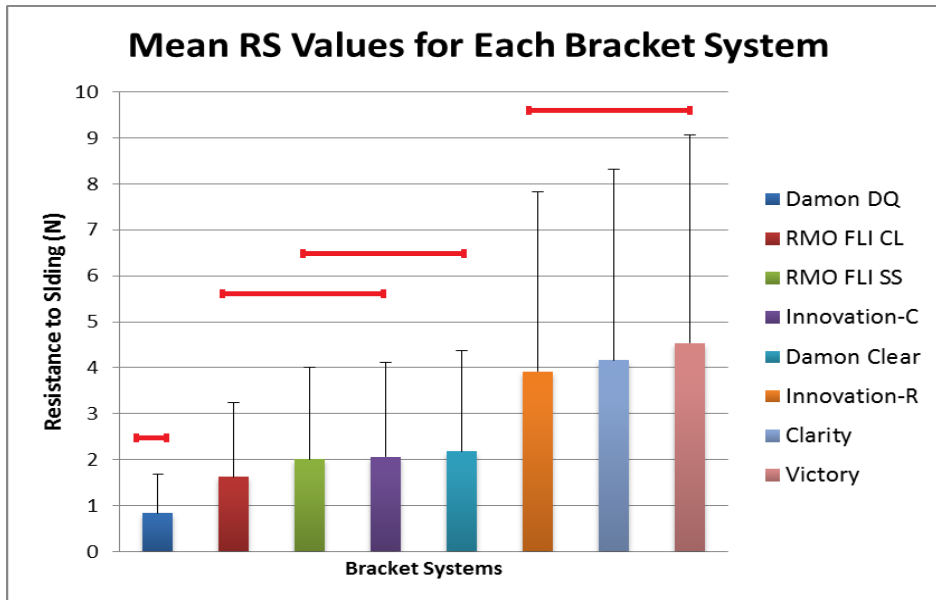


Figure 4. Mean Resistance to Sliding Values for Each Bracket System

Self-ligating bracket systems: RMO FLI CL, RMO FLI SS and Innovation-C had similar sliding resistances, which were significantly higher than the sliding resistance for Damon DQ. No significant differences in sliding resistance were observed between RMO FLI SS, In-Ovation-C and Damon Clear, however, RMO FLI CL had significantly lower sliding resistance than Damon Clear. Conventional bracket systems, Clarity and Victory produced similar sliding resistances. In-Ovation-R had sliding resistances similar to the conventional bracket system (Clarity), but lower sliding resistance than the Victory bracket system. Overall, the self-ligating bracket systems (Damon DQ, RMO FLI CL, RMO FLI SS, In-Ovation-C, and Damon Clear) had significantly lower sliding

resistances compared to conventional bracket systems (Clarity, Victory) and one self-ligating bracket system (In-Ovation-R) using the 0.019 X 0.025-in rectangular fiber reinforced composite archwire (See Figure 5).

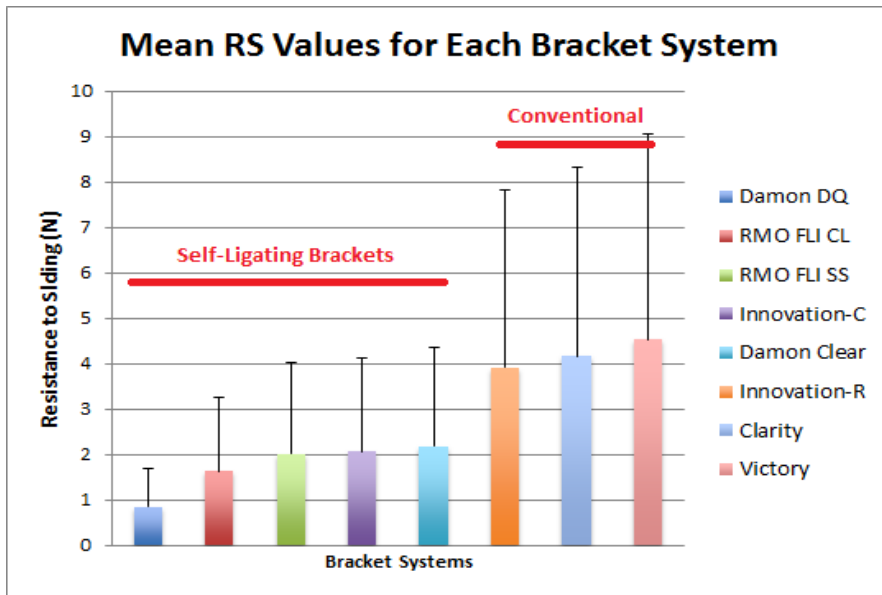


Figure 5. Mean Resistance to Sliding Values for Each Type of Bracket System

Each bracket angulation (0° , 2.5° , 5° , 10°) displayed a significantly different resistance to sliding (See Figure 6). A significant increase in sliding resistance was observed as bracket angulation increased irrespective of the bracket system ($F = 653.74$, $p \leq 0.0005$, See Table 3, Figure 6). The bracket angulation with the lowest resistance to sliding was zero degrees (0.696 ± 0.754 N), while the greatest RS was observed at ten degrees of bracket angulation (5.182 ± 1.897 N).

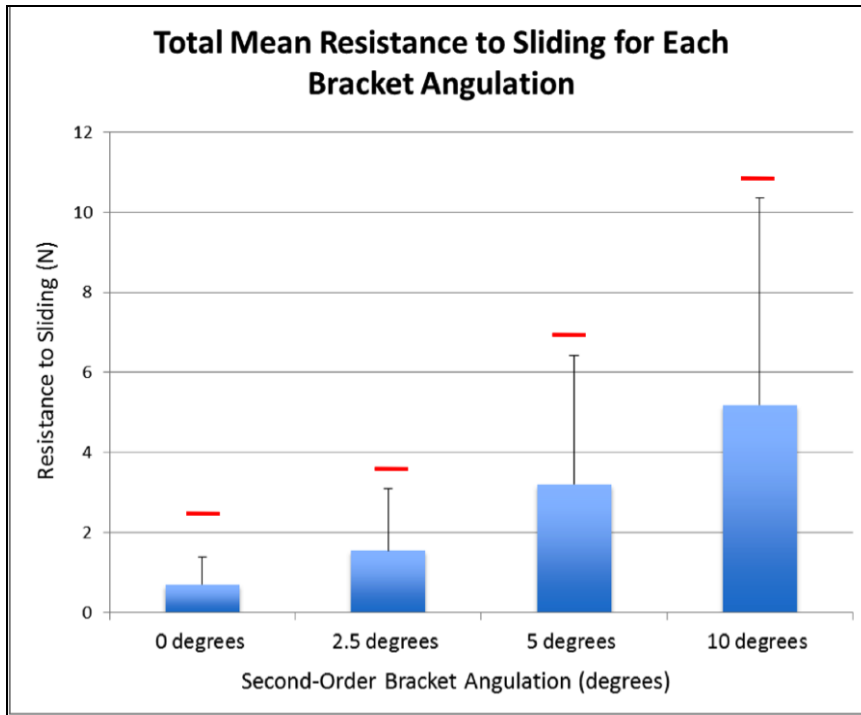


Figure 6. Total Mean Resistance to Sliding for Each Bracket Angulation (Annotated)

A significant interaction was observed between bracket system and bracket angulation ($F = 8.210$, $p \leq 0.000$, See Table 3). The largest interaction ($> 1N$) occurred between conventional bracket systems, Clarity and Victory (between 2.5° , 5° , and 10° of bracket angulation), self-ligating bracket system, RMO FLI CL and In-Ovation-C, (between 5° and 10° of bracket angulation), and self-ligating bracket system in-Ovation-R and conventional bracket system Clarity (See Figure 7).

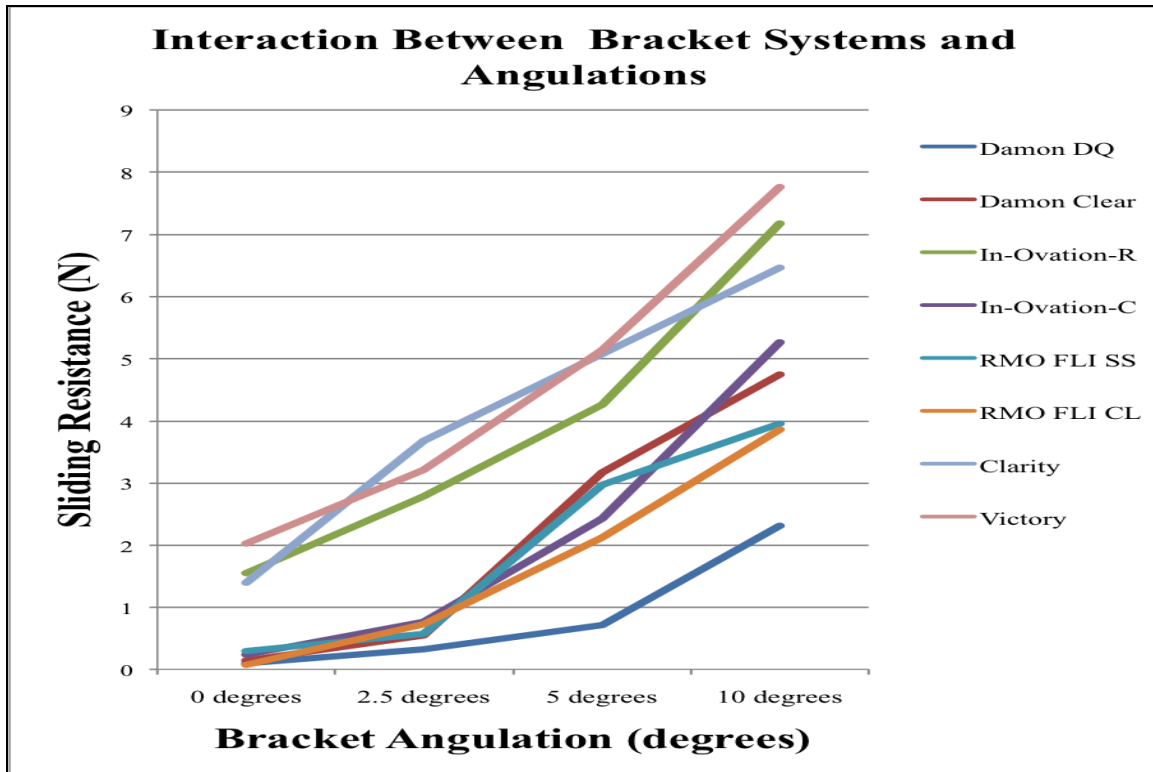


Figure 7. The Interaction of Bracket Systems and Bracket Angulation on Sliding Resistance (measured in Newtons)

Microscopic analysis of the archwire segments revealed increased archwire wear as the bracket angulations increased. Damon DQ had the least amount of abrasive wear compared to the other bracket systems. The abrasive wear appeared to be limited to the surface coating of the archwire and archwire integrity was maintained for all test samples for each bracket system tested.

VII. DISCUSSION

Effect of the Bracket Ligation Method on Resistance to Sliding

The sliding resistances generated for bracket systems increased in the following order: Damon DQ < RMO FLI CL, RMO FLI SS, and In-Ovation-C < Damon Clear < Innovation R, Clarity < Victory. The findings in this study seem to support the general finding of reduced sliding resistance due to reduced ligation forces for self-ligating brackets compared to conventional bracket systems using elastomeric ligature ties. However, one self-ligating bracket, In-Ovation-R, displayed elevated sliding resistances similar to conventional bracket systems.

The In-Ovation bracket series has a passive-active design, where a labial rhodium clip actively engages the archwire at dimensions larger than 0.018 X 0.018-in and passively retains archwires below this dimension. Thus, the 0.019 X 0.025-in FRC archwire used in this study should be actively engaged at each bracket angulation tested, which may explain the increased sliding resistance for In-Ovation-R compared to the other self-ligating bracket systems. In our study, In-Ovation-R produced RS values similar to the conventional bracket systems, Victory and Clarity. Henao and Kusy⁵⁸ also reported that In-Ovation-R bracket systems produced significantly less friction than conventional brackets when coupled with 0.014-in archwires, however this difference was not seen for larger archwire dimension, 0.016 x 0.022-in and 0.019 X 0.025-in.

Interestingly, the ceramic self-ligating bracket system, In-Ovation-C, produced significantly lower RS values than its stainless steel In-Ovation-R bracket. Given the similarity in bracket design, our findings must reflect some other difference between the

brackets. Voudouris et al.³⁸ also found that the In-Ovation-C bracket generated significantly lower sliding resistance than In-Ovation-R with 0.019 x 0.025-in stainless steel archwires. They determined that the labial chromium-cobalt (CR-CO) clips within In-Ovation C had more freedom and a reduced size compared with In-Ovation-R, which reduced binding forces on the archwire.³⁸

Effect of Bracket Composition and Design on Resistance to Sliding

Bracket composition and design have been shown to influence sliding resistance. Each self-ligating bracket system evaluated in this study had rounded edges of the bracket slot to reduce archwire binding as bracket-archwire angulations increased. Rounded bracket edges may provide a particular benefit for fiber reinforced composite archwires by limiting the abrasive wear resulting from their reduced hardness when used with ceramic or metal bracket materials. In addition to slot design, slot dimensions can also influence the resistance to sliding. Some studies suggest that frictional resistance decreases as slot size increases.⁴⁵ Other studies have shown that the increased inter-bracket distances of narrow bracket designs allow greater freedom for the archwire to pass through angulated bracket.⁵⁹

The passive self-ligating bracket system, Damon DQ (stainless steel), had the lowest sliding resistance of all bracket systems evaluated. The reduced sliding resistance for Damon DQ at each bracket angulation tested may result from the increased vertical slot dimension (0.0243") and narrow bracket design (0.112"), compared to the other self-ligating bracket systems with 0.022" vertical slot dimensions.⁶⁰ Because of the oversized vertical slot dimension of the Damon brackets, the critical contact angle needed to initiate binding was increased. These differences in slot dimension of Damon DQ may

explain the reduced resistance to sliding.

Despite a similarity in bracket design, the ceramic self-ligating bracket, Damon Clear, had greater sliding resistance than its stainless steel sibling Damon DQ. The increased sliding resistance for Damon Clear may be the result of increased roughness of the ceramic material. Also, the ceramic bracket has a larger bracket width (0.137-in) and a reduced vertical slot dimension compared to Damon DQ. This may also reduce the sliding resistance. Furthermore, the ceramic passive self-ligating bracket system, RMO FLI CL, produced significantly lower resistance to sliding compared to the ceramic self-ligating bracket, Damon Clear. Both bracket systems have passive self-ligating designs and similar polycrystalline alumina (ceramic) composition. The explanation for the reduced resistance to sliding with RMO FLI CL is not likely to be caused by a difference in bracket width given their similarity (0.135” RMO FLI CL , 0.137” for Damon Clear). This difference may be explained by a difference in the labial clip used to secure the archwire. RMO FLI has a polymer labial clip to secure the archwire, while Damon Clear has a nickel titanium spring retained slide for archwire retention. The nickel titanium spring may have exerted more force as bracket angulation is introduced compared to the polymer clip, which could deform or proved less binding at similar bracket angulations.

Effect of Bracket Angulation

There was a significant increase in resistance to sliding as bracket angulation increased. Damon DQ had the lowest frictional resistance of all the bracket systems tested. Overall the self-ligating bracket systems had a lower sliding resistance than the conventional bracket systems and In-Ovation-R. The increased sliding resistance for the

conventional bracket systems and In-Ovation-R is likely to be related to the increased force of archwire ligation. In this study, elastomeric ligatures were used to secure the archwire in the bracket slot for conventional bracket systems. Elastomeric ligatures were chosen because they delivered more predictable forces of ligation compared to stainless steel ligature ties. As bracket angulation increased and the critical contact angulation was exceeding binding occurred and the resistance to sliding dramatically. The reduced sliding resistance for Damon DQ compared to all of the other bracket systems is likely attributed to its increased critical contact angle. As shown in the literature, smaller bracket widths and larger bracket slots allow greater freedom of the archwire to bend before binding at the bracket edges occur.⁵⁹ The reduced sliding resistance for self-ligating brackets seems to support previous findings, which show increased critical contact angulations for self-ligating brackets compared to wider conventional bracket systems.³¹

Abrasive Archwire Wear

After analyzing the fiber reinforced composite archwires for wear, it was determined that archwire penetrations were limited to the coating surfaces of the archwire specimens, leaving the underlying glass fibers intact. Similar to results published by Zufall and Kusy,¹¹ this finding implies that the risk of glass fiber release during clinical use has been reduced or eliminated with the use of archwire coatings. Microscopic analysis of the archwires revealed more archwire wear as bracket angulations increased, with the least wear occurring at zero degrees and the greatest wear occurring at ten degrees. Although there was no significant difference in the amount of wear between

stainless steel and ceramic bracket systems, more wear was observed with ceramic bracket surfaces.

The archwire fracture was observed at the ends of the cut wire segments. The fractures did not propagate through the tested wire segments, however glass fiber segments were clearly visible and exposed through the protective wire coating. These exposed wire segments could be a potential hazard in the clinical setting if fragments are released into the oral cavity. This is particularly relevant because most archwires must be cut to length to prevent excessively long wires from extending beyond the last bracketed tooth to avoid soft tissue damage. Currently, the manufacturer advises that the archwires be cut with a distal-end cutter. Even if the archwire is cut outside the mouth the wire can still release glass fibers into the oral cavity over time. One possible solution would be to make all archwire cuts outside the patient's mouth and then seal the cut end of the archwire with a bonding agent or composite.

Explanation of Interaction

There were several interactions that occurred between the bracket systems and bracket angulations with respect to sliding resistance ($F = 8.21$, $p \leq 0.0005$, See Table 4, Figure 3). The largest interactions (approximately 1.3 Newtons) with the greatest likelihood of having clinical relevance were observed between five and ten degrees of bracket angulation for the bracket systems tested. The largest interaction among bracket systems occurred between Victory and Clarity, In-Ovation-R and Clarity, and RMO FLI SS and In-Ovation-C. While it's uncertain if these observed interactions were clinically

significant these results may prove relevant for understanding trends in sliding resistance for the tested archwire and bracket systems as it relates to tooth movement.

One conventional bracket system, Clarity, produced greater sliding resistance at two and a half degrees of bracket angulation compared to Victory (See Figure 3). However, Clarity produced lower sliding resistance at five and ten degrees of bracket angulation compared to Victory. The increased hardness of stainless steel brackets may cause greater notching of the softer composite archwires at higher bracket angulations compared to the ceramic material used to compose the Clarity bracket system, but this trend was not observed with other bracket systems tested. The bracket width and design are similar for both bracket systems and unlikely to have contributed to these differences in sliding resistance. The observed difference may be the result of increased binding at the adjacent brackets for Victory, as these brackets were a different type as compared to the central cuspid bracket. These brackets may have increased sliding resistance due to increased binding by the elastomeric ligature at each bracket angulation tested. Further analysis with similar adjacent brackets would be required to explain this interaction, however, limitations in the amount of archwire samples available prohibited analysis at this time.

The self-ligating bracket system, RMO FLI SS, produced lower sliding resistances as the bracket angulation was increased from five to ten degrees compared to In-Ovation-C. The explanation for this reduced sliding resistance in RMO FLI SS bracket may be related to the narrower bracket width (0.114”) compared to In-Ovation-C (0.134”), however this is unlikely as reducing the bracket width allows greater inter-bracket distance thereby increasing the archwire’s freedom to move before contacting the

edges of the bracket slot, as discussed by Creekmore.⁵¹ The increased sliding resistance for In-Ovation-C is likely caused by the passive-active labial clip, which actively binds the archwire at sizes greater than 0.18-in X 0.18". As archwire angulation increases, the contact between the labial clip increases, resulting in an elevated sliding resistance for the In-Ovation-C bracket compared to the RMO FLI SS bracket at ten degrees. The same interaction is also observed between In-Ovation-R and the conventional bracket system, Clarity. This may explain why the manufactures of Biomers® prohibit the use of the active self-ligating bracket system (SmartClip) with their wires.

Clinical Significance of Study Results

In summary, when considering fiber reinforced composite archwires, passive-self ligating brackets with narrow bracket widths and increased vertical slot heights may provide decreased resistance to sliding. It appears that either stainless steel or ceramic bracket materials can be used with rectangular FRC archwires in an 0.019- X 0.025-in dimension, although abrasive wear may progress faster with a ceramic bracket surface. Generally speaking, if sliding mechanics are performed when the teeth are well aligned (at bracket angulations below the critical contact angulation), self-ligating brackets may provide a lower sliding resistance than conventional brackets or active self-ligating brackets. Thus, if similar amounts of force are applied to both types of brackets (conventional and self-ligating) a greater portion of force is effectively used to produce tooth movement with most self-ligating bracket systems. However, the reduced sliding resistance by bracket systems with oversized slot dimensions, such as Damon DQ may come at the expense of controlling tooth movement.

In the case of FRC composite archwires, the reduced abrasion of archwire may be a sufficient enough reason for some practitioners to consider a passive self-ligating bracket over an active self-ligating bracket or conventional bracket system to provide increased patient safety. This decision may have little effect on treatment time. As previous research has highlighted, archwire properties may have more influence on the sliding resistance than any individual bracket system.²⁷

Study Limitations

Like all In vitro studies this study cannot accurately recreate the clinical conditions of the oral environment such as: forces of mastication, saliva, temperature, bone remodeling by the periodontal ligament, plaque accumulation, biofilm absorption, and enzymatic degradation, which can affect resistance to sliding.⁴⁴ Furthermore, laboratory conditions cannot simulate the oral environments' aging effect on orthodontic appliances over time. Despite these shortcomings, the information gained from laboratory studies may offer insight into the mechanics and behaviors that we see clinically.

In addition, it is impossible to reproduce physiologic tooth movement that occurs in response to biologic processes between the periodontal ligament and the alveolar bone because the appropriate rate of tooth movement occurs around 1mm per month. The simulated in-vitro rate of tooth movement (0.5mm to 10mm per minute) is 21,700 to 425,000 times faster than what occurs clinically.⁶¹ Because of these limitations, clinicians should be cautioned that in-vitro findings, although a useful guide to anticipated clinical behavior, cannot adequately predict or explain observed clinical performance.⁶²

Finally this three-bracket model system may not adequately reflect clinical conditions. In this study resistance to sliding was tested with respect to bracket angulations (tipping), while the effects of bracket prescription and position in different planes of space were ignored. The influence of bracket movement in these other planes may also impact the resistance to sliding values. Also, the inter-bracket distance was increased in this study in order to reduce the influence of sliding resistance at the adjacent brackets. Increasing the inter-bracket distance may have resulted lower forces of sliding resistance compared to shorter inter-bracket distances found clinically. Also, this study analyzed the archwire segments after only one test run each which may not provide adequate time to determine how archwire integrity would degrade after multiple runs. Archwires may be exposed to repeated archwire wear during orthodontic treatment, which could increase the chances of wear and potential fracture. Further study and long term testing are needed to better understand fiber reinforced composite archwire with respect to sliding resistance and durability for orthodontic tooth movement.

Future Research

The utilization of different bracket materials may also prove beneficial in reducing the sliding resistance of FRC archwires. Composite brackets were popular in the past but lost favor due to concerns with staining, fatigue, and surface roughness. Composite brackets possess a similar hardness as FRC archwires, which may prove beneficial for reducing sliding resistance, as these materials are less likely to notch the softer FRC archwires compared to the harder stainless steel and ceramic brackets. Finally, in vitro studies cannot mimic the natural oral environment, thus an in vivo study using the rectangular FRC wire in clinical practice would be ideal to evaluate the

esthetics and efficacy of FRC wires during sliding mechanics. To date, no one has evaluated FRC wires in the oral environment to determine the validity of the laboratory findings in the literature.

New polymers are being developed for esthetic orthodontic archwire that may offer some advantages to existing FRC archwires. Burstone et al.⁶ evaluated new high-strength self-reinforced (SRP) polyphenylene polymers archwires of round and rectangular cross sections that capable of accepting bends similar to stainless steel archwires. These archwires were determined to have consistent cross-sectional dimensions, high spring-back, and similar strength to smaller titanium archwires.⁶ Additionally, polyphenylene polymer can be formed into desired shapes by heat forming or cold forming. Currently, no studies have evaluated the sliding resistance or archwire integrity of polyphenylene archwires. The overall stiffness of polyphenylene is higher than traditional thermoplastics, such as polycarbonate. Polyphenylene esthetic archwires have six times the stiffness compared to FRC composite archwires.⁶⁴ The increased stiffness of polyphenylene esthetic archwires may overcome the weakness in shear forces and limited secondary formability inherent to FRC wires. The increase in stiffness (decreased modulus) results in greater sliding resistance as bracket angulation increases.⁶

Similar to esthetic FRC archwires, the introduction of polymer reinforcement to bracket materials may improve the properties compared to ceramic and stainless steel materials. Bazakiduo et al.³² found that composite brackets with elastomeric or stainless steel ligation produced lower sliding resistance compared to ceramic and stainless steel brackets. Furthermore, Esthetic FRC composite self-ligation brackets have been reported to have lower friction than other esthetic brackets materials (ceramic and composite).⁶⁵

This study does not compare composite bracket materials, however, such an-evaluation may prove beneficial in producing a more esthetic bracket material with RS values lesser or equal to stainless steel or ceramic bracket systems.

VIII. SUMMARY & CONCLUSIONS

This study compared the resistance to sliding characteristics of rectangular 0.019 x 0.025" fiber reinforced composite archwire in an angulated three-bracket model system, using self-ligating and conventional bracket systems. The bracket systems included six self-ligating brackets (Damon DQ, Damon Clear, RMO FLI SS, RMO FLI CL, In-Ovation-R, and In-Ovation-C) and two conventional brackets systems (Clarity & Victory).

The following conclusions can be drawn from this investigation:

- 1- A passive self-ligating bracket system, Damon DQ, exhibited the lowest sliding resistance of all bracket systems tested, using the rectangular 0.019 X 0.025" fiber reinforced composite archwire by Biomers® SimpliClear.
- 2- Overall, self-ligating bracket systems produced lower sliding resistance compared to conventional bracket systems tied with elastomeric ligatures (Victory & Clarity) and one passive-active self-ligating bracket system, In-Ovation-R.
- 3- Sliding resistance increased significantly as bracket angulation increased.
- 4- The Damon DQ bracket demonstrated a larger critical contact angle (~ 5°) compared to both the conventional (<2.5°) and other self-ligating bracket systems (~ 2.5°) tested in this study.
- 5- No conclusive statements can be made regarding the difference in sliding resistance for ceramic compared to stainless steel bracket materials.

- 6- Biomers® SimpliClear rectangular 0.019 x 0.025” fiber reinforced composite archwires (Torque A) maintained its glass fiber integrity while being drawn through angulated brackets, however, microscopic analysis revealed increased wear and abrasion of the coating material as bracket angulations increased.

When considering the results of this study, it is important to note that statistically significant findings may not imply clinical relevance. However, these results may give some insight into the behavior and trends among different bracket systems, which could prove useful to clinicians when deciding among similar bracket systems to use with fiber reinforced composite during sliding resistance.

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