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Friction Testing of Contemporary Self-ligating Appliance Systems

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Abstract

Background: Resistance to tooth movement is multifactorial, with friction (FR) one of many important components. There is limited data comparing contemporary Passive and Active self-ligating bracket (SLB) systems in terms of FR created by archwire engagement. **Aim**: To compare classical FR in contemporary SLB systems and traditional twin brackets *in vitro*, and to identify the point of initiation of bracket-archwire engagement. **Materials & Methods**: Nine bracket systems of .022-in slot size were FR tested: Victory Series (3M Unitek) with elastic ligature (control); Passive SLB systems Damon Q (Ormco), Carriere SLX (Henry Schein), H4 (Ortho Classic), Altitude SL (Rocky Mountain Orthodontics, RMO), and Empower2 Passive (American Orthodontics, AO); Active SLB systems Victory Series SL (3M Unitek), Speed (Speed System Orthodontics), and Empower2 Active (AO). Single upper right central incisor brackets were mounted on a custom metal fixture and straight sections of various round and rectangular Nickel Titanium (NiTi) archwires (.016, .018, .018 x .018, .020 x .020, .016 x .022, .017 x .025, .019 x .025, and .021 x .025-in) were ligated to the bracket and FR was measured with an Instron Universal Testing Machine. Ten unique tests utilizing a new bracket and new archwire were conducted for each group in the dry state. **Results**: FR was significantly different between control, Passive SLB and Active SLB systems ($p < 0.0001$). Passive SLB groups had no mean difference of FR between bracket systems. Each Active SLB group exhibited significant mean differences in FR depending on the bracket system and archwire shape and dimension. Active SLBs possess a distinctly different pattern of initiation of FR engagement between bracket and archwire depending on the system. **Conclusions**: FR between the archwire and bracket slot differs between Passive and Active SLB systems. Understanding the different bracket-wire interactions of SLB systems helps the clinician understand and plan biomechanics with the bracket system of their choice.

Keywords: Friction, Self-ligating brackets, Active, Passive, Orthodontics

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List of Abbreviations

AO	American Orthodontics
ANOVA	Analysis of Variance
A-Emp	Empower2 Active
A-Spd	Speed
A-Vic	Victory Series SL
BI	Binding
C-Vic	Victory Series
FR	Friction
-in	Inch
NiTi	Nickel Titanium
NO	Notching
OSIM	Orthodontic Simulator
PDL	Periodontal Ligament
P-Alt	Altitude SL
P-Car	Carrier SLX
P-Dmn	Damon Q
P-Emp	Empower2 Passive
P-H4	H4
RS	Resistance to Sliding
RMO	Rocky Mountain Orthodontics
SEM	Scanning Electron Microscope
SLB	Self-ligating Bracket
SS	Stainless Steel
SD	Standard Deviation

Chapter 1
Review of Literature

1.1 Introduction

In order to meet the expectations of the patient, orthodontic treatment must be efficient. The pursuit of an appliance that reduces treatment time has been the goal of orthodontic innovations since Edward Angle moved from a stiff wire E arch to a more flexible appliance in order to engage more teeth at the same time using the ribbon arch. The beginning of the modern era of orthodontics began with the introduction of the pre-adjusted straight-wire appliance from Andrews. Appliance design and treatment biomechanics are closely interrelated. The straight-wire appliance minimized wire bending during finishing. However, it was soon recognized that new treatment biomechanics and force levels were required to treat cases effectively.[1] With a similar thought process, the reintroduction of self-ligating bracket (SLB) systems has grown in popularity over the past two decades attempting to decrease friction and increase treatment efficiency. However, in order to express proper in-out, tip and torque prescription of the brackets, the archwire must also engage within the bracket slot. Thus, the use of clinical biomechanics varies between clinicians using different orthodontic systems due to force systems required by specific brackets.

1.2 Friction

Friction (FR) is the force resisting the relative lateral motion of elements in contact. It is derived from the electromagnetic force between charged particles. FR can be subdivided into dry, fluid, skin, and internal FR. In orthodontics, FR is determined by conditions of equilibrium of all the forces acting on the tooth-bracket-archwire complex. Only microscopic peaks called asperites make contact with one another when two solid surfaces slide across one another. This system is considered to be in the category of dry FR where two solid surfaces in contact resist relative lateral motion.[2] Dry FR can further be classified as static or kinetic FR. Static FR is between two objects not moving relative to each other. Its magnitude is equal to that required to oppose motion until motion begins. Kinetic FR occurs when two objects are moving in relation to one another. Kinetic FR is usually less than static and it is less relevant in orthodontics since teeth are not in continuous motion along an archwire.[2] Teeth move at approximately 1mm per month which makes analysis of static FR more relevant in orthodontics.[3]

Resistance to tooth movement involves more than FR alone. Nanda has described more than twenty variables and factors that affect this interaction in the mouth.[4] Due to the complexity of interactions in tooth movement, *in vivo* measures of FR in the oral environment are difficult and rare. However, many *in vitro* studies have investigated key interactions and effects of bracket geometry,[5,6] material properties,[7,8] ligation method,[9,10,11,12,13] tooth angulation,[5,14,15,16] position of adjacent teeth,[17,18] effect of saliva,[7,19,20,21] and perturbation.[22,23] Resistance to sliding (RS) is the effect of several of the above mentioned effects which become dominant at different angles of second-order rotation.[24]

1.2.1 Orthodontic Resistance to Sliding

Kusy and Whitley[5,7] propose that RS is a combination of simple classical FR, binding (BI), and notching (NO) expressed as, Equation 1:

Equation 1: RS = FR + BI + NO

In this case, FR will occur at tip angles less than 3.7° and is due to FR caused by ligation of the wire into the bracket slot.[5] When the tip angle exceeds the critical value of 3.7°, BI is the dominant interaction where FR increases due to the wire contacting the opposing mesial-distal edges at the end of each slot. These opposing forces create a moment and FR becomes a product of the tip angle of the bracket to the wire as well as the bracket width. As bracket width decreases for a given couple, the FR force increases. High angles of tip will cause physical interlocking of the wire and bracket, caused by permanent deformation of either surface that will cause a very high, non-FR based resistance called NO. At this point, RS increases unpredictably to an extent that at such angles sliding ceases.[24] It has been long known that RS increases as the contact angle between bracket and archwire increases.[25] Thorstenson and Kusy calculated that for a 0.018 x 0.025-in stainless steel (SS) archwire, an activation of 6° was clinically most relevant, since beyond that angle, archwire uprighting forces would cause the tooth to “walk” along the archwire in a series of binding and releasing movements around this angle.[8,13,21] BI has been found to equal or exceed FR once angulation exceeds 3°. Studies demonstrate that BI can contribute up to 80% of RS at 7° angulation and 99% at 13° for stainless steel archwire with a ceramic bracket.[16]

1.3 Ligation

1.3.1 Conventional Elastomeric Ligation

Orthodontic treatment with a fixed appliance involves the use of metal, ceramic, or plastic brackets in combination with metal archwires. The archwire is affixed into the bracket slots with ligatures around tie wings. Historically, the archwire was ligated to each bracket with SS wire, however, alternative methods were developed due to the length of time these ligatures took to place. A biocompatible elastomeric polymer in the shape of a circular ring was developed by Drs. Anderson and Klein in the late 1960's to ligate the archwire to the bracket.[26] Elastomeric ligatures were quickly accepted and adopted into practice due to their ease of placement and reduction of required chair time. Due to the high coefficient of FR between polyurethane ligatures and metal archwires, alternative designs have been developed in order to facilitate reduced movement of archwire along the brackets. Development of low FR elastomeric ligatures has been attempted with hydrophilic coatings, injection silicone molding, and altering the shape of the ligatures in order to decrease the coefficient of FR. The Slide ligature (Leone Orthodontic Products, Sesto Fiorentino, Firenze, Italy) is one such nonconventional elastomeric ligature that is manufactured with a special polyurethane mix by injection molding. When attached to an orthodontic bracket, its shape allows the archwire to passively slide through the slot with reduced frictional resistance.

1.3.2 Self-ligation

In the mid-1930s, SLBs were first introduced in the form of the Russell attachment by Stolzenberg.[27] The bracket had a flat-head screw which seated the archwire in its slot as the threaded screw tightened into the circular face of the bracket. The Russell attachment allowed the bracket to act in either the active or passive state depending on if the screw completely seated the wire against the base of the slot (active) or allowed it to move freely within the slot (passive). The core features of SLBs include security of ligation, rapid archwire changes and lower RS (Figure 1).

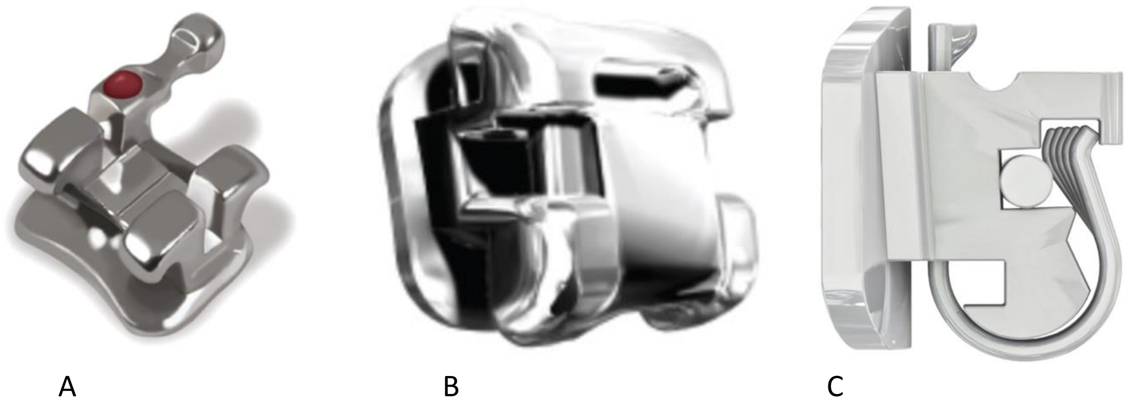

Figure 1: A. Traditional twin bracket (Victory Series, 3M Unitek); B. Passive SLB characterized by sliding door mechanism (Damon Q, Ormco); C. Active SLB characterized by sliding clip mechanism with an archwire range that can be passive within the slot or engaging the clip in active phase (Speed, Speed System Orthodontics).

Contemporary SLBs contain an integrated mechanism to attach an archwire. “Active” SLBs often utilize a clip ligation mechanism to engage the archwire into the slot while “Passive” SLBs utilize a door ligation mechanism that allows the archwire to be free within the slot. Passive SLBs make any BI component a high percentage of the overall RS. In Passive SLBs, the FR is usually close to zero making the BI component constitute essentially 100% of the resistance to sliding.[28] Studies of initial aligning wires placed in irregularly aligned brackets have shown large reductions in RS with SLBs in all 3 planes of space.[12,17,29] Many claims regarding the advantages of Passive SLB orthodontic appliances have been made, primarily regarding reduced treatment time due to less FR and lower force systems. Due to the complexities and vast combination of factors that interplay during orthodontic movements, the vast majority of *in vitro* studies simplify their methodology to record one-dimensional frictional data.

1.3.3 Reduced Resistance to Sliding in Self-ligating Brackets

There are no current *in vivo* studies of FR between bracket and archwire. However, many *in vitro* studies have addressed the question of FR between bracket and archwire. Franchi *et al*.[12]

reported lower FR for Passive SLBs Carriere SL (Henry Schein), Damon 3MX (Ormco), and nonconventional elastomeric ligatures (Slide, Leone Orthodontic Products) on a conventional bracket system compared to twin edgewise brackets tied with conventional elastomeric ligatures. A recent systematic review,[9] demonstrated multiple studies indicating that the Damon II SL (Ormco) bracket possesses lower FR resistance than conventional bracket systems.[30,31,32,33,34,35] Early on, Loftus *et al*.[36] concluded that FR forces of Damon SL brackets were similar to that of traditional twin metal or ceramic (with steel slot) brackets. Henao and Kusy[37,38] demonstrated Damon II SL brackets produced significantly diminished FR than conventional brackets on small round archwires and greater FR on rectangular archwires. Similarly, Griffiths *et al*.[39] described Damon brackets having lower RS compared with ceramic conventional brackets. Tecco *et al*.[40] reported Damon II SL brackets having lower FR than that of conventional brackets, but similar to conventional brackets with nonconventional elastomeric ligatures (Slide) on .016 NiTi archwires. Interestingly, as archwire changed to rectangular and increased in diameter, the nonconventional ligatures produced less FR compared to Damon brackets and traditional brackets with conventional elastomeric ligatures. A comparison between the Passive Damon 3MX SLB and Active SLBs (Speed, Speed System Orthodontics; In-Ovation R, Dentsply GAC; Time 2, AO) demonstrated that the Speed SLB had the greatest amount of frictional forces with multiple round and rectangular wires, while often there was no significant difference in FR forces between Damon 3MX, Time 2, and In-Ovation R bracket systems.[41] Additionally, a study comparing FR of Passive Damon 3MX SLB, Passive Smartclip (3M Unitek), Active Empower SLB (AO) and conventional twin orthodontic brackets (AO) with elastomeric ligatures on .016-in NiTi and .019 x .025-in SS, demonstrated that the Damon 3MX showed significantly less FR than other groups on both archwires.[42]

Distinctly different force distributions have been found to exist between SLBs and conventional brackets with various 3-dimensionally simulated malocclusions. Force distributions using simulating modeling have found Passive SLBs to demonstrate small force vectors of posterior teeth in a distal buccal direction compared to large force vectors of the anterior teeth in a buccal direction with conventional brackets.[43,44,45,46,47,48] The reduced RS in SLB systems is hypothesized to minimize incisor flaring during alignment by increasing arch perimeter with distal buccal movement of posterior teeth. A study comparing pre- and post-treatment models treated with Damon 3MX and a conventional edgewise appliance (Dentsply GAC), using different archwire materials and sequence, observed significantly more transverse expansion from the canines to molars and similar incisor proclination, post-treatment with the Damon system.[49] This study did not support the hypothesis that incisor flaring can be reduced with posterior teeth augmented in the distal buccal direction. However, it would be surprising if these marked differences in force distribution resulted in no clinical consequences.

1.4 Reported Advantages of Self-ligating Brackets

Several consecutive case series studies found that treatment with SLB systems was quicker, less painful, and required less visits while providing similar alignment and occlusion as conventional systems.[9,50,51,52] However, other similar studies,[49,53,54] and many randomized controlled studies,[55,56,57,58,59,60] have found no difference in terms of treatment time or pain between SLBs and conventional brackets in various points of the treatment process. Recent systematic reviews looking at the summary of claims versus evidence concluded that SLBs do not reduce overall time in treatment or pain.[61,62] However, SLBs were found to save on average twenty seconds per arch in chair side ligation time, and have a final mandibular incisor alignment inclination of 1.5° less than conventional systems for treatment.[63]

1.5 Stages of Orthodontic Treatment

Raymond Begg suggested that comprehensive orthodontics could be sequentially divided into three major stages of treatment.[64] The stages are: (1) alignment and leveling, (2) correction of molar relationship and space closure, and (3) finishing. During the first stage of treatment, alignment and leveling, an initial archwire should be placed that will provide light continuous force to produce the most efficient tipping tooth movements.[65] Heavy forces are avoided and as such, light resilient round archwires made from superelastic NiTi are often utilized. The initial wires bring the malposed teeth into the arch and are progressively changed to larger dimension wires to level the arches into a flat plane. Root movement is not needed in this stage, and thus, rectangular archwires are normally avoided. Proffit[65] states that the archwire should be able to move freely within the bracket during this stage. Since the tooth movements required at this stage are optimized by wires that are free to move in the bracket slot, low FR levels are a characteristic that would enhance this stage of orthodontic treatment.

The second stage of treatment is concerned with obtaining an optimal occlusion of buccal segments in the anteroposterior plane of space while closing extraction or residual spaces in the arches. As previously mentioned, space closure involved with sliding mechanics involves RS which is comprised of the total effects of FR, BI, and NO. It has been contested that BI is the major contributor to RS in Passive SLBs only because FR is essentially zero.[28] Regardless of which is the primary determinant of RS, FR plays a partial role in the second stage of orthodontic treatment where minimal RS forces are optimal.

The final stage of orthodontic treatment, finishing, is characterized by root movement to obtain ideal torque as well as adjustments of individual teeth to obtain ideal relationships that may be lacking due to discrepancies produced in either bracket placement or appliance prescription.[65] A characteristic of this final stage is the engagement of large square or rectangular archwires such that the built-in prescription of the orthodontic bracket can be expressed. For this to occur, the wire must be fully engaged within the slot of the orthodontic bracket, as opposed to the first stage of treatment, where archwire play was desirable. Thus, high FR values would be representative of this stage if a full expression of the bracket prescription is desired. As such, comprehensive orthodontic care is often characterized initially by low force levels with smaller FR values and progresses to finishing stages that requires greater control with bracket-wire engagement with higher FR values.

1.6 Bracket-Wire Engagement

The engagement of the bracket-archwire complex is a critical component of orthodontic biomechanics and tooth control. Rapid initial alignment will occur with low forces generated between the bracket and wire. FR-free mechanics can be achieved using loosely tied SS ties to twin brackets or with SLBs.[66] In the straight-wire technique, orthodontic brackets are programmed with first- (horizontal labio-lingual in-out, rotational), second- (vertical mesial-distal tip/angulation) and third- (labio-lingual root/crown torque) order prescriptions which are expressed with the interaction between bracket and archwire. This interaction is dependent on wire geometry and size. The freedom between the bracket slot and archwire is known as “play”.

In order to express first- and third-order prescription, the bracket closure mechanism must hold the archwire against the base of the slot. Otherwise, should the archwire be in a passive position, the in-out, rotational, and torque component of the bracket prescription will not be realized (Figure 2). For good first- and third-order control, the bracket closure mechanism must hold the archwire against the base of the slot. Engagement of the archwire in the bracket slot by ligation methodology develops FR but does not affect BI or NO. BI and NO is a component of second-order prescription, which is affected by bracket width, inter-bracket span, wire size, and material composition rather than by ligation method.[67]

When an undersized archwire is inserted into a bracket slot, the wire can rotate clockwise or counterclockwise around the long axis of the archwire.[68] In an .022-in bracket slot, a .019 x .025-in working wire will have 9° of play before third-order engagement will occur.[69] Additional torque is built into the bracket prescriptions such that an ideal resultant torque will be expressed with commonly utilized finishing archwires. For the clinician utilizing SLBs, it is important to have a thorough understanding of wire engagement for improved control and finishing.

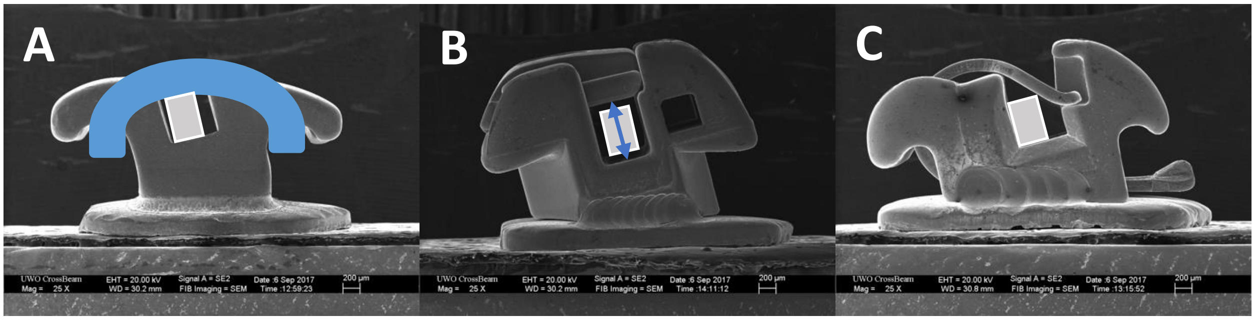

Figure 2: A. Victory Series bracket with representative elastomeric ligature pressing a hypothetical rectangular archwire into base of slot; B. Passive Damon Q bracket showing first-order play; C. Active Empower2 bracket with archwire pressed into the base with active clip.

Since the development of SLBs, there has been a debate over whether they should have an active or passive ligation mechanism. Proponents of an active clip suggest that it provides a ‘homing action’ on a deflected wire and provides more control with the appliance.[70] Active SLBs typically have a passive slot depth ranging between .0175 to .020-in. With small round wires, the bracket is passive, but with larger wires the flexible clip seats the archwire to the base of the bracket slot. Passive SLBs typically have a slot depth of 0.028-in and do not force the wire to the base of the slot. It has been suggested that Passive SLBs produce less FR, which may result in decreased control compared to Active SLBs.[71] A study examining two Active (In-Ovation and Speed) SLBs and two Passive (Damon 2 and SmartClip) SLBs found active brackets expressed greater torque values than Passive SLBs due to the active clip forcing the wire into the bracket slot.[72] In this study, the clinically applicable range of torque activation was greater for the Active SLBs than for the Passive SLBs. The study of bracket-archwire engagement primarily examines third order torque control by defining engagement angles on large dimension rectangular archwires.[71,72] An in-depth understanding of bracket-wire FR in terms of initiation of Active SLB wire-engagement may assist the clinician in understanding when first and third order prescription is starting to express. Due to the large volume of orthodontic bracket systems and archwire combinations, a comprehensive understanding of bracket-wire engagement is lacking.

1.7 Methods to Study Orthodontic Friction

FR can be a simple element of orthodontics to investigate. However, FR which simulates the true intraoral 3-dimensional interactions is very difficult to measure. Due to simple design, the vast majority of research consists of *in vitro* studies to eliminate compounding variables, but leave numerous limitations.[2] Most studies utilize passive systems to investigate FR where the effects of BI and NO have been removed. These studies mount brackets so that the wire is pulled through a parallel slot without introducing angulation between wire and bracket (Figure 3). These studies measure the amount of FR between the wire, bracket, and the ligation device. However, the limitations to this study methodology are that brackets are seldom placed in passive positions relative to one another in clinical conditions.

Active *in vitro* investigations study FR with varied angulations between archwire and brackets in relation to each other. Studies utilizing 2-dimensional and 3-dimensional FR with varied degrees of displacement have been completed. Recognized limitations include the inability of the malaligned brackets to move and the inability to measure forces at individual teeth.[12,35]

Figure 3: A. Set up of passive *in vitro* FR study[3]; B. Passive *in vitro* FR study utilizing multiple aligned brackets.[6]

Recently, a 3-dimensional orthodontic simulator (OSIM) was developed capable of accurately measuring forces and moments applied by orthodontic fixed appliances on up to 14 teeth simultaneously. The OSIM utilizes six-axis load cells to measure forces and moments on individual teeth. The OSIM is used to model and measure the simultaneous force and moments of full arch continuous archwire systems. A study by Badawi *et al*.[43] was designed using the OSIM specifically to examine the force system at the bracket-wire interface with an emphasis not to simulate the oral environment. The authors noted that this model does not control for intraoral variables such as moisture, occlusion, lip pressure, tongue pressure, PDL compliance, alveolar bone level and geometry. The same research group also developed an orthodontic FR simulator to specifically examine sliding mechanics.[24] In this model, the six-axis load cell measures forces and moments on an individual bracket during archwire sliding and second order rotations.

1.8 Summary of Issues

The relevant literature of studies examining the magnitude of forces developed during engagement of archwires into the slot of conventional and SLBs is limited.[48] Many FR studies exist for conventional twin, Passive and Active SLB systems. However, the majority of previous research examines a comparison of either twin brackets to Passive Damon SLBs or compares Passive Damon SLBs to Active SLB alternatives (Speed, In-Ovation, Empower) without including a conventional twin bracket to give a gauge of relativity of the forces. Additionally, due to the large volume of potential bracket-archwire combinations, the majority of studies either limit their study to looking at only a few bracket systems, or only utilize a few sizes of archwires. One of the most inclusive FR studies examined two Passive and two Active SLBs with a conventional twin control, but were only able to compare seven of twelve archwire combinations suggested by each bracket manufacturer.[38] By not examining the same wires between groups, it makes it difficult to compare bracket systems to one another. Additionally, bracket systems are continuously changing and there is no current data regarding a comparison of contemporary Passive Damon Q (Ormco) to many of the alternative contemporary Passive and Active SLB systems (3M Unitek Victory Series SL; Ortho Classic H4; Henry Schein Carrier SLX; AO Empower2; RMO Altitude SL; Speed System Orthodontics Speed) on varied small to large round, square and full size rectangular archwire.

1.9 Purpose of Current Investigation

The purpose of the current investigation is to compare classical FR between contemporary SLB systems and traditional twin brackets *in vitro*. This information will help to identify the point of initiation of bracket-archwire engagement for tested SLB systems.

1.10 Hypothesis

- Passive SLB systems are not different compared to one another in terms of FR, but have less FR than Active SLBs and conventionally ligated brackets.
- Active SLB systems produce differing amounts of FR compared to each other on varied wire sizes and dimensions.

Chapter 2
Materials and Methods

2.1 Orthodontic Brackets

Nine bracket systems of 0.022-in slot size were tested. The control was a Victory Series twin bracket with elastomeric ligature (item #854-660; AO); Passive SLBs included, Damon Q, Carriere SLX, H4, Altitude SL, and Empower2 Passive; Active SLBs included, Victory Series SL, Speed, and Empower2 Active (Table 1). Brackets were chosen from well-known orthodontic manufacturers based on bracket popularity, availability, and lack of previous published FR literature. The bracket prescription utilized was the most popular available in the specific system being tested.

Ligation System	Test Group	Bracket System	Bracket Manufacturer	Bracket Item Number	Reported Bracket Slot Size (in)	A-NiTi Archwires Tested (in)	Wire Manufacturer	Wire Item Number
Elastic Ligatures (Control)	C-Vic	Victory Series	3M Unitek	017-876	0.022	0.016		
Active Self-Ligation	A-Vic	Victory Series SL	3M Unitek	025-302	0.022 x 0.028	0.018		
	A-Spd	Speed	Speed System Orthodontics	22UR1+17HR-	0.022 x 0.028	0.018 x 0.018		SENT016
	A-Emp	Empower2 Active	American Orthodontics	485-1117	0.022 x 0.028	0.020 x 0.020		SENT018
						0.016 x 0.022		SENT1818
						0.017 x 0.025	G & H	SENT2020
						0.019 x 0.025	Orthodontics	SENT1622
						0.021 x 0.025		SENT1725
Passive Self-Ligation	P-Dmn	Damon Q	Ormco	491-6460	0.022 x 0.028			SENT1925
	P-Car	Carriere SLX	Henry Schein	713-309-10	0.022 x 0.028	0.019 x 0.025		SENT2125
	P-H4	H4	Ortho Classic	916.2001-10	0.022 x 0.026	0.021 x 0.025		
	P-Alt	Altitude SL	Rocky Mountain Orthodontics	M11400	0.022 x 0.028			
	P-Emp	Empower2 Passive	American Orthodontics	585-1117	0.022 x 0.028			

Table 1: Investigated orthodontic brackets and archwires.

2.2 Imaging Bracket Morphology

Prior to FR testing, morphologies of the brackets were examined using a scanning electron microscope (SEM; Zeiss 1540XB) at 20 keV and recorded as micrographs and analyzed with Zeiss SmartSEM (Carl Zeiss Microscopy GmbH; Jena, Germany). Four new brackets from each system were cleaned with acetone and 95% ethanol and mounted on studs using carbon adhesive tabs. Side-view micrographs of the brackets taken at 75X magnification were utilized to measure the minimum slot height and depth.

2.3 Friction Testing

All as received brackets were mounted onto transfer mounting pins using the custom fabricated bracket mounting jig displayed in Figure 4. Single upper right central incisor brackets were mounted on transfer pins with Assure Plus (item #PLUS; Reliance Orthodontic Products) and Transbond XT (item #712-031; 3M Unitek) adhesive, allowing an .0215 x .025-in SS wire to passively fit (item # 03 125-58; GAC International) to negate tip and torque variation between bracket systems.

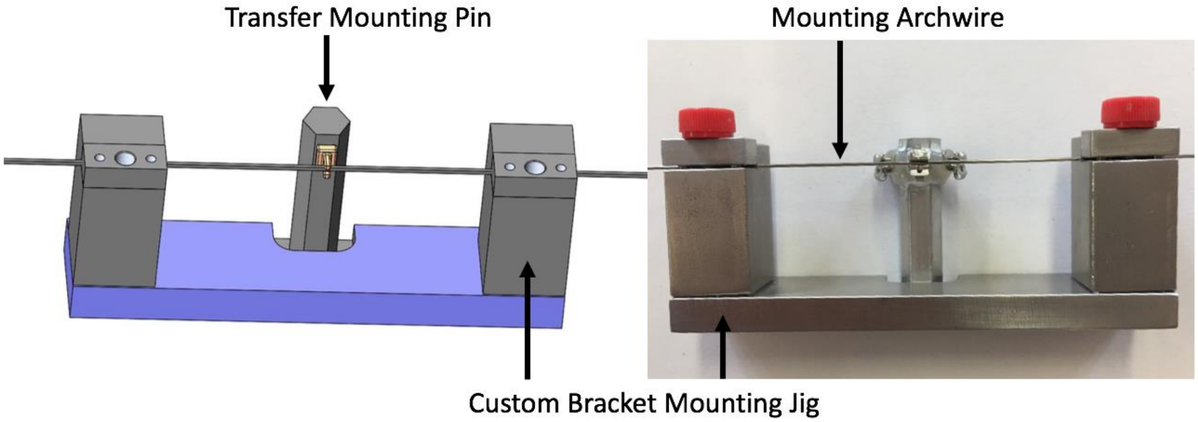

Figure 4: Custom fabricated bracket mounting jig with fixed mounting archwire and removable transfer bracket mounting pin.

Transfer pins were moved to a custom fabricated Instron mounting fixture as in Figure 5. Straight sections of various round, square and rectangular austenitic NiTi archwires (Table 1) were secured on-center to the archwire mounting clamp. Prior to use, archwires were measured with a digital caliper (item #0400-EEP; Ortho-Pli) and were all consistently 0.001-in less in dimension than reported by the manufacturer. Wires were ligated to the brackets and FR was measured with an Instron Universal Testing Machine (Instron Model #3345; Norwood MA, USA) with Series IX/s Software (Instron; Norwood MA, USA). All as received brackets and wires were handled with gloves such to not introduce contaminations.

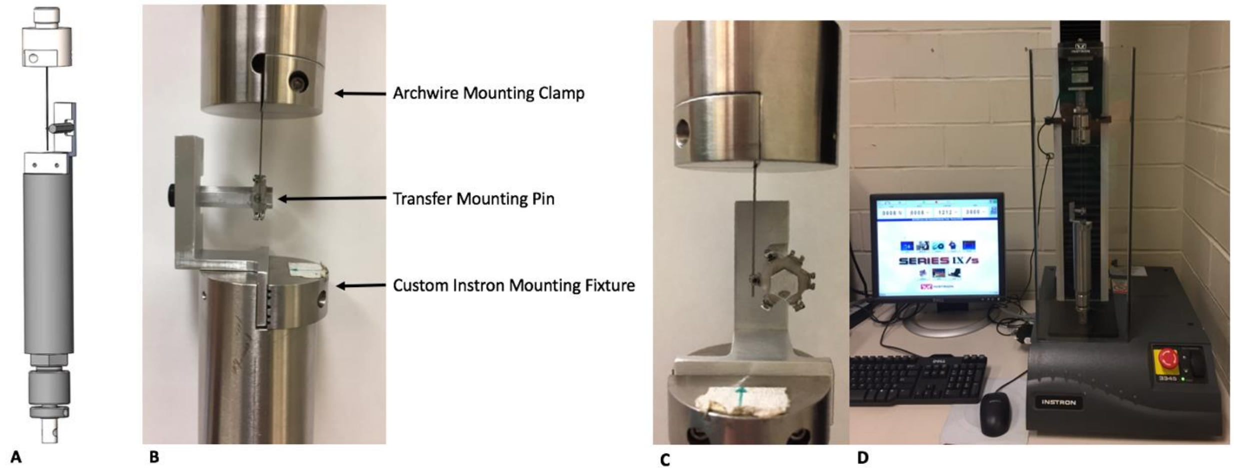

Figure 5: Digital model of custom fabricated Instron mounting fixture, A. Frontal view of archwire mounting clamp holding centered wire to transfer mounting pin with bracket mounted on custom Instron mounting fixture, B. Side view of custom set up, C. Instron testing machine with bracket mounting fixtures, D.

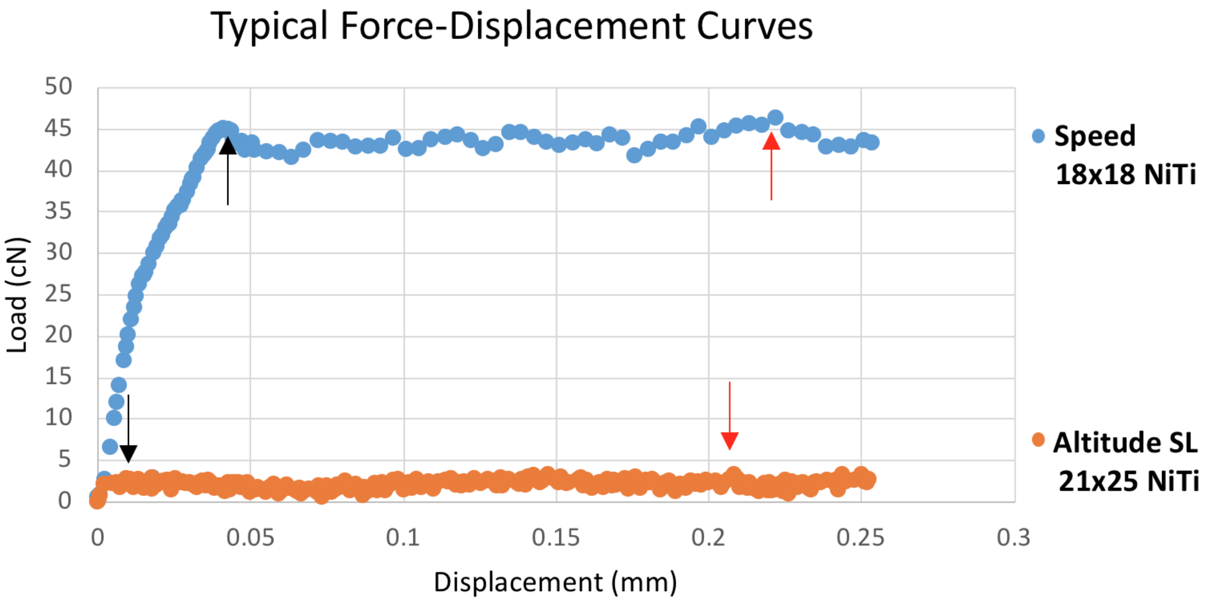

Figure 6: Typical FR plot of force versus displacement for two experimental runs. The black arrow denotes possible peak static FR and the red arrows denote the recorded maximum FR values.

The Instron testing machine was employed with a 10 N load cell that was set on a range from 0 to 5 N to determine the FR force levels. In order to improve recordings of low FR values, the archwire mounting clamp was designed to incorporate an additional mass of 295.5 g (~3 N) which was then calibrated such that recordings would produce true values. FR was recorded in centiNewtons (cNs) noting that 1 cN equals 1 g. As described by Tecco *et al.,*[73] each wire was pulled through the bracket slot by a distance of 0.25mm at a speed of 0.5mm per minute and the maximum value was recorded. Our initial goal was to measure peak static FR; however the peak static FR value was not always discernable at low force levels (Figure 6). As such, the maximum force value was chosen instead of peak static FR as described in other reports.[73,74] After each test, the Instron testing machine was stopped, the transfer mounting pin turned to a new bracket, used archwire cut, and upper unit lowered so that the wire could be ligated to the new bracket. Ten unique tests utilizing a new bracket and new wire segment were conducted for each group in the dry state as suggested in previous studies.[20,21,24]

2.4 Data Analysis

Descriptive statistical information, including mean and standard deviation (SD) was calculated for each bracket-archwire combination. Once it was recognized that the two largest wires produced essentially no FR with the Passive SLBs, smaller wires were deemed unnecessary to test. The FR values were analyzed with statistical software (SPSS Statistics 23.0; SPSS, Inc., Chicago, IL) using two-way analysis of variance (ANOVA) with Bonferroni adjustment for multiple comparisons to compare significant differences between groups ($P < 0.05$). Independent variables (bracket and archwire) did not possess an interaction with one another ($P > 0.05$).

Chapter 3
Results

3.1 Imaging Orthodontic Bracket Morphology

Imaging of brackets (Figure 7) with SEM allowed accurate measurement of slot dimensions (Figure 8) in the closed-door state as described in Table 2. The manufacturer reported slot dimensions for all brackets was .022 x .028-in, except for the P-H4 bracket which the manufacturer reports to have an .022 x .026-in slot size. SEM measurement at 75x magnification showed the P-H4 brackets to possess a .022 x .028-in slot size rather than the manufacturer claimed dimensions. Additionally, the P-Alt brackets appear to have larger slot dimensions than reported with greater variability than other Passive SLBs. The remaining brackets were very close in dimension to those reported by the manufacturers.

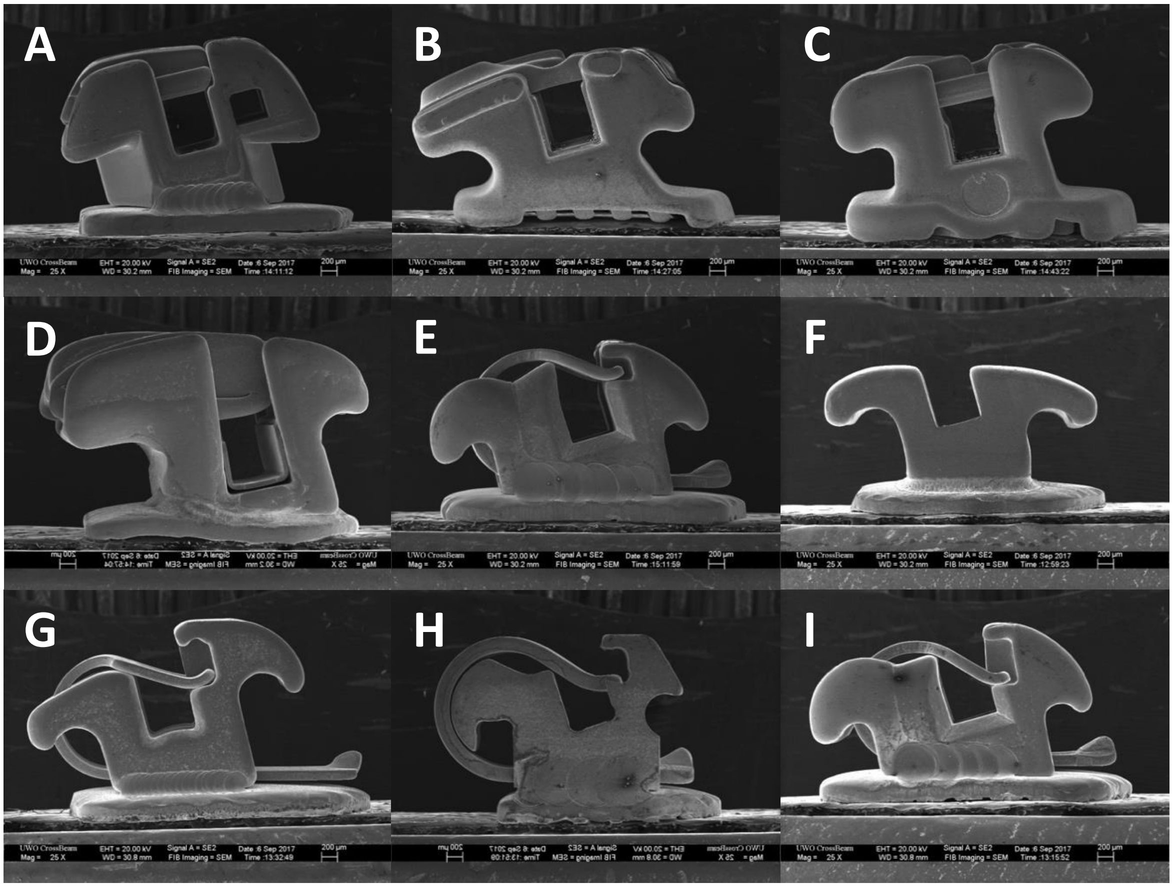

Figure 7: SEM imaging at 25x magnification of P-Dmn, A; P-Car, B; P-H4, C; P-Alt, D; P-Emp, E; C-Vic, F; A-Vic, G; A-Spd, H; A-Emp, I.

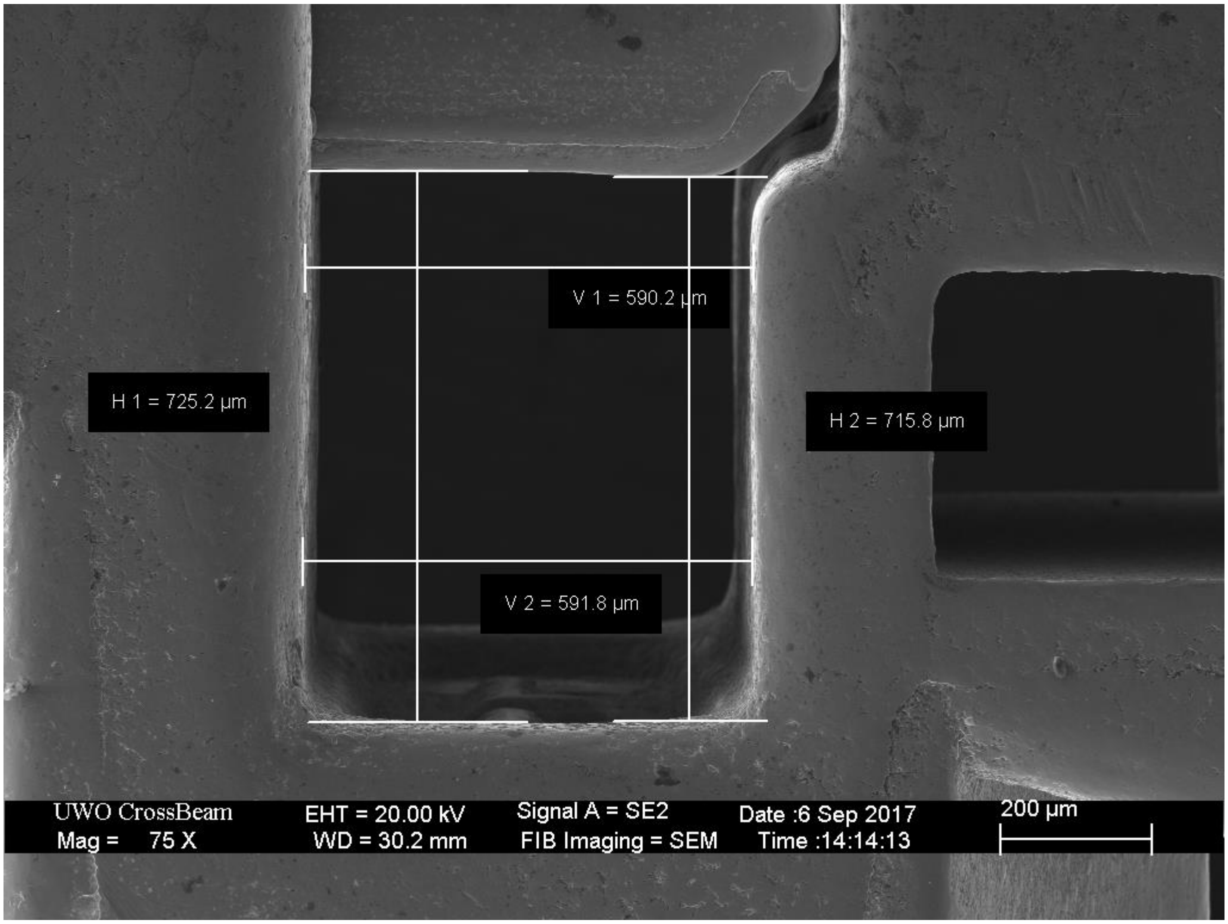

Figure 8: SEM imaging at 75x magnification for measurement of P-Dmn slot dimensions.

Bracket Group	Minimum Slot Height (in)	Minimum Slot Depth (in)
P-Dmn	0.0231 ± .0001	0.0282 ± .0002
P-Car	0.0231 ± .0003	0.0307 ± .0002
P-H4	0.0234 ± .0002	0.0285 ± .0001
P-Alt	0.0243 ± .0006	0.0326 ± .0005
P-Emp	0.0234 ± .0001	0.0264 ± .0003
C-Vic	0.0232± .0004	0.0253 ± .0006
A-Vic	0.0237 ± .0001	0.0189 ± .0004
A-Spd	0.0230 ± .0001	0.0153 ± .0006
A-Emp	0.0231 ± .0001	0.0140 ± .0003

Table 2: Minimum bracket slot height and depth measures from SEM at 75x magnification. Data are mean measurement values ± SD, n = 4 for each bracket.

3.2 Friction

Passive SLB groups had minimal FR with significantly (P < 0.001) lower mean FR than control C-Vic brackets (Figure 9). Passive SLB groups demonstrated no significant (P > 0.05) differences of mean values between systems regardless of archwire (Figure 9). Passive SLBs demonstrated significantly lower mean FR than all Active SLBs with .019 x .025 and .021 x .025-in NiTi wires (P < 0.001).

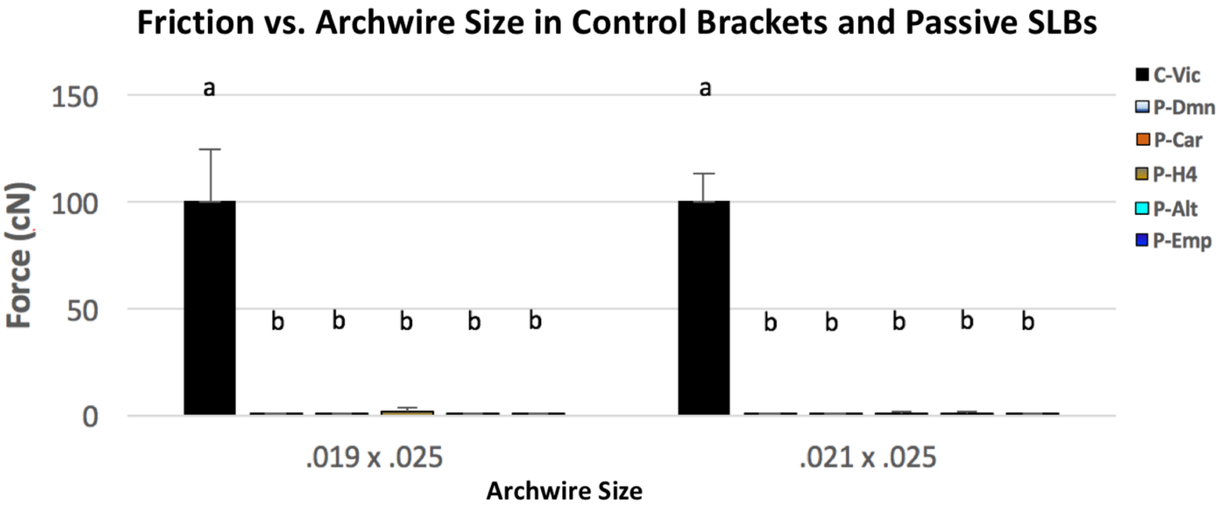

Figure 9: Minimal FR forces measured across all Passive SLB groups. Data are mean FR values ± SD, n = 10 for each bracket/wire combination. Non-significant differences at P > 0.05 between brackets by two-way ANOVA with Bonferonni post hoc test are denoted by the same letter.

Active SLB groups exhibited significant mean differences in FR compared to control C-Vic brackets (P < 0.01) on every archwire as well as distinctly different patterns of mean FR compared to each other, depending on archwire shape and dimension (Figure 10). All Active SLBs demonstrated significantly less mean FR than controls until the .019 x .025 and .021 x .025-in NiTi wires (Figure 10). Compared to controls on these archwires, the FR levels are maintained at significantly diminished levels for the A-Vic and A-Spd brackets, while the A-Emp bracket forces were significantly increased (Figure 10).

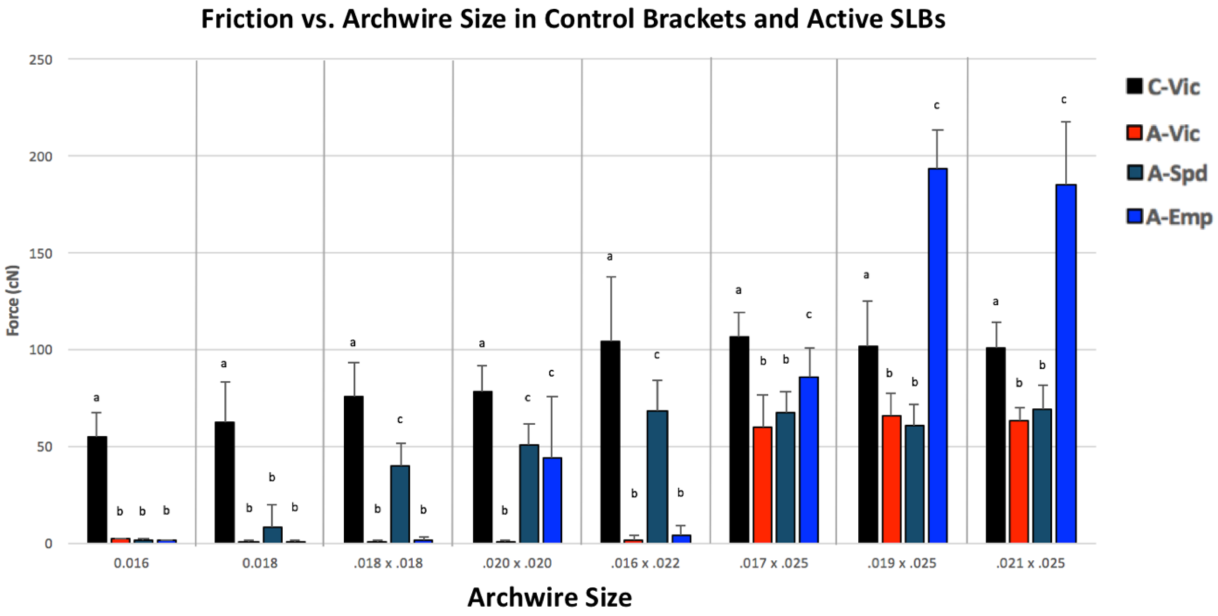

Figure 10: Comparison of FR between control brackets and Active SLBs on varied archwires. Data are mean FR values ± SD, n = 10 for each bracket/wire combination. Non-significant differences at P > 0.05 between brackets by two-way ANOVA with Bonferonni post hoc test are denoted by the same letter.

All Active SLBs demonstrated minimal FR values on each tested round archwire (Figures 10 & 11). Compared to the .016 NiTi wire, the A-Vic bracket had no mean significant increase in FR engagement when changing from round to square archwire but began to exhibit a distinctly significant increased FR beginning on .017 x .025-in NiTi (Figure 11). Compared to the .016 NiTi, the A-Spd bracket-wire engagement initiates significant mean increase in FR on the .018 x .018 and .016 x .022-in NiTi (Figure 11). Compared to the .016 NiTi, the A-Emp bracket-wire engagement initiates distinctly significant mean increases in FR on the .020 x .020, .017 x .025, and .019 x .025-in NiTi wires (Figure 11).

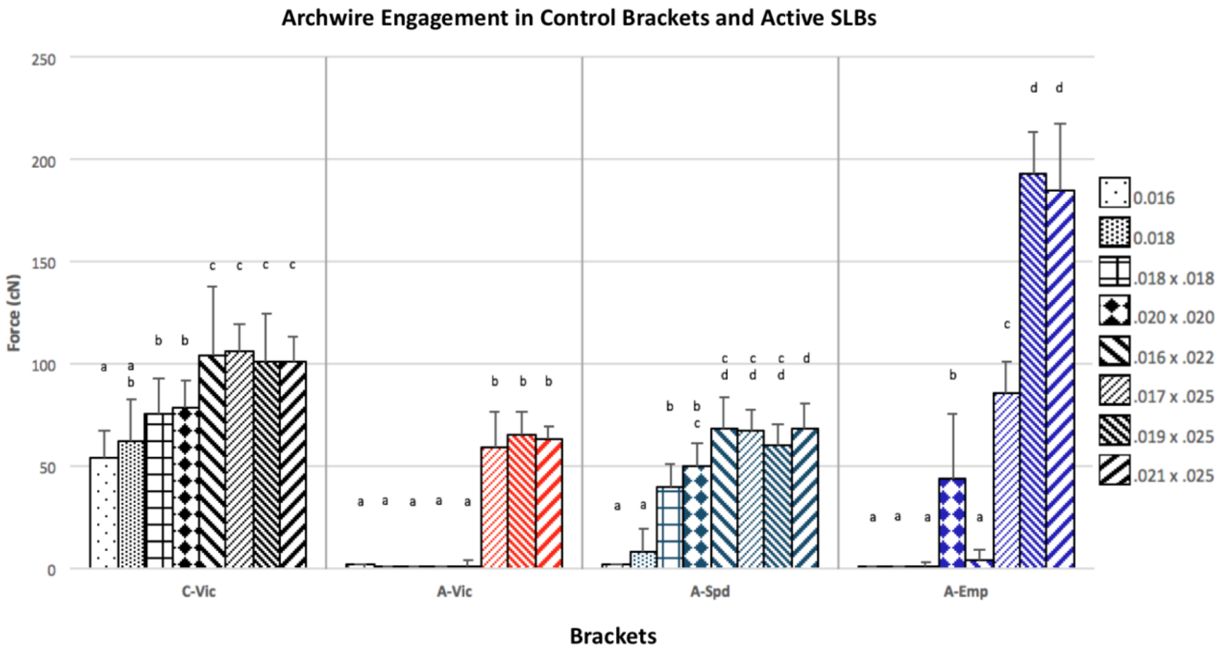

Figure 11: Comparison of FR between archwires on control brackets and Active SLBs. Data are mean FR values ± SD, n = 10 for each bracket/wire combination. Non-significant differences at P > 0.05 within each bracket system by two-way ANOVA with Bonferonni post hoc test are denoted by the same letter.

Chapter 4
Discussion

The aim of this investigation was to identify and compare the differences in classical FR of contemporary SLBs to traditional twin brackets, and in doing so, identify bracket-archwire engagement points for SLB systems. Unlike existing studies that have examined FR, this investigation explored a more extensive collection of current contemporary SLB manufacturers with a large variation of archwires. This is important to the clinician who utilizes any of the studied bracket systems for planning biomechanics and utilizing the prescription of the orthodontic system in finishing.

4.1 Orthodontic Bracket Morphology

Examination of the bracket morphology suggests that bracket quality in terms of precision is very good in general but can be varied. Our initial assessment of bracket morphology found that the P-Alt had a mean dimension of .024 x .033-in rather than .022 x .028-in suggested by RMO. The SEM micrographs visually demonstrate that there appeared to be variation in the position of the bracket slot insert on the P-Alt brackets, in terms of depth of seating, which likely lead to such discrepancy in slot dimension. Additionally, the P-H4 bracket is reported to be .022 x .026-in, while mean measurements of .023 x .028-in were observed. This suggests that there may be greater slot tolerances in this bracket than previously thought. Reports examining SLB slot heights suggest a considerable variability of between 3% to 15% larger slot sizes than nominal values from the manufacturer.[75,76] Consistent with existing literature, our findings observed variability in the slot tolerances. However, this did not seem to affect their performance since FR was similar among all of the tested Passive SLBs.

4.2 Methodology to Study Orthodontic Friction

The brackets in this study were mounted in a manner to zero the tip and torque of the brackets such that classical FR described by Kusy[5] could be examined without introducing BI or NO effects. Passive *in vitro* FR studies are advantageous when determining the amount of FR contributed by the wire, bracket, and ligator without other variables involved. The variables considered in this study included archwire dimension and shape as well as bracket system and bracket ligation modality. BI and NO are components of second-order movement, of which, ligation device has little effect.[2,77]

There exists no gold standard of methodology to study orthodontic FR. A linear model was chosen for this study since the primary purpose of this examination was to study classical FR between SLBs and archwire and to remove as many confounding variables as possible. In trial runs, it was quickly recognized that precision bracket mounting would be necessary in order to conduct a FR study that examined very low force levels. Similar to previous reports, a custom fabricated mounting apparatus was constructed both to mount the brackets and to conduct this study with the Instron Universal Testing Machine.[3,6] Additionally, a 10 N load cell was utilized to measure and record force values. Our initial pilot studies revealed that FR measurements found in this study (0.4 – 200 cN) were not producing smooth curves, and rather appeared like noise and variability. Alternative options of obtaining a 5 N load cell or fabricating a custom load cell were contemplated in order to address the issue of accurately recording low force values. The challenge was ultimately addressed by adding 295.5 g (approximately 3 N) to the upper clamp apparatus connected to the load cell. This effectively made it such that the load cell did not have to measure force levels at the lower limit of its capabilities.

The crosshead speed of 0.5mm/min was based on the work of Tecco *et al*.[6,31,40] allowing adequate acquisition of data points. Analysis of static FR is more relevant in orthodontics since teeth move at such a slow rate.[3] However, the peak between static and kinetic FR was not always discernible, particularly with the Passive SLBs recording means between 0.4 – 1.6 cN. Similar to other studies examining FR values very close to zero in SLB systems, we recorded maximum kinetic FR values rather than peak static FR values.[73,74] However, it appears in our study that there was very little relevant difference between peak static FR and maximal kinetic FR from a clinical perspective.

This current FR study was conducted in the dry state. Previous studies have found that artificial saliva was not a good substitute for human saliva.[20] Additionally, the utilization of saliva was found not to significantly influence the loads generated during sliding mechanics regardless of ligation method.[20,21,24]

It has been reported that FR tests with elastomeric modules can be repeated five times using the same ligature with no statistical difference in FR.[78] Additionally, it has been shown previously, that multiple testing has no adverse effects on bracket-wire couples.[79] Moreover, a recent orthodontic FR study found no differences on analysis of force displacement data with the multiple reuse of orthodontic brackets with new wires.[80] However, in the present study, each test was repeated 10 times with a new bracket and new wire segment in an effort to improve reproducibility due to the multiple variables being examined which is consistent with other previous reports.[10,30,41]

4.3 Friction

A direct comparison of the various studies on the topic of FR would be complex due to differences in experimental settings, acquisition systems, points of force application, and differences in bracket-wire angulations.[30] Ideally, a gold standard in orthodontic FR testing would be established similar to that proposed by Fathimani *et al*.[24]. However, this proposed methodology has not been universally accepted in published literature and does not have wide spread utilization. Previous studies utilizing single bracket FR testing in a linear system have reported similar ranges of FR values. Similar to our control findings, Cacciafesta *et al*.[30] reported that .022 Victory Series kinetic FR values ranged between 45 to 70 cN on .016 and .019 x .025-in NiTi, respectively. Additionally, in concordance with our findings, Thorstenson and Kusy[8] reported that using .016 x .022 and .019 x .025-in NiTi, FR of Speed Active SLBs was 60 and 72 cN, respectively. Moreover, similar to our findings on Passive SLBs, Thorstenson and Kusy[8] also reported that the FR of Damon 2 brackets was 0.15 cN on .019 x .025 NiTi.

In agreement with the hypothesis, this study indicates that both Active and Passive SLB systems produce different degrees of FR and in differing amounts on varied archwire sizes and dimension. The current study revealed that all examined Passive SLB systems had low levels of FR on full size NiTi wires. Once these findings were observed with the .019 x .025-in NiTi and confirmed with .021 x .025-in NiTi, then a decision was made to not test smaller archwires on the Passive SLBs as they would also be near zero. These finding are consistent with Franchi *et al.*[12] who reported lower FR for Passive SLBs Damon 3MX (Ormco) and Carriere SL (Henry Schein) compared to twin edgewise brackets tied with conventional elastomeric ligatures. Conversely, Henao and Kusy,[37,38] reported that Damon II SL brackets produced diminished RS compared to conventional brackets on round wires, but greater FR on rectangular archwires. The Henao and Kusy studies,[37,38] utilized a mounted typodont and pulled preformed NiTi archwires through misaligned brackets to test RS which includes the effects of BI, NO as well as FR. Unlike the Henao and Kusy studies,[37,38] our research was focused on measuring classical FR by utilizing a linear study model. It has been shown that Damon 3MX SLB have less FR on .016 and .019 x .025-in SS than Active Empower SLB.[42] Our study is in accordance with these previous findings with the additional finding that the P-Emp bracket has similar FR as a P-Dmn bracket. To date, there are no studies that have compared this many contemporary Passive SLBs in terms of FR.

Each of the Active SLBs demonstrated a unique FR profile throughout the archwire sequencing. All of the Active SLBs acted passively with the tested round NiTi wires. The A-Vic bracket acted passively until it engaged on the .017 x .025-in NiTi wire and then maintained a consistent FR similar to the A-Spd bracket on .017 x .025, .019 x .025, and .021 x .025-in rectangular wires. The A-Spd bracket was the only Active SLB to engage the .018 x .018 square and .016 x .022-in rectangular NiTi wires. It has been reported that the A-Spd bracket has the greatest amount of FR compared to Passive Damon 3MX, Active SLB Time2 and In-Ovation R.[41] The limitation of this previous study was that it did not test conventional twin brackets with elastomeric ligatures to gain relativity of their results.

Our findings indicate that the A-Emp bracket has the greatest amount of FR once .019 x .025 and .021 x .025-in NiTi is engaged. This significantly increased FR was greater than control C-Vic brackets and approximately twice as much FR as that found in the A-Vic or A-Spd. Prior to these full size NiTi wires, the A-Emp bracket initiated FR engagement on .020 x .020-in square and .017 x .025-in rectangular NiTi and had reduced levels of FR compared to controls. The A-Emp bracket acted similar to Passive SLBs on tested round, .018 x .018, and .016 x .022-in NiTi wires. Certainly, the Active SLB systems have unique FR profiles when compared to each other and to conventional twin brackets with elastomers, or Passive SLBs. The findings suggest an ability to utilize low FR passive mechanics with round and moderately sized square or rectangular archwires and then increase FR engagement to express first- and third-order bracket prescriptions using larger dimension rectangular wires should the clinician require it.

4.4 Clinical Applications

There are many proponents of both passive and active biomechanics in orthodontics. This study assists the knowledge base for both of these clinical groups. To the proponents of completely Passive SLBs, this study demonstrates that in terms of FR, there exist many similar options to choose from in terms of Passive SLBs. The FR-free clinician will ultimately have to make their choice of Passive SLB based on cost, comfort, debond rate, durability, and ability to finish cases well with prescription expression. For the proponents of Active SLBs, this study demonstrates the unique subtleties between bracket systems in terms of FR and the ability to begin archwire engagement. Knowledge of the present study should allow the Active SLB clinician to distinctly utilize both FR-free and active-FR biomechanics while progressing through the stages of orthodontic treatment.

The straight wire appliance was developed by Andrews to minimize archwire bending during finishing. This is accomplished by integrating first-, second-, and third-order prescription into the bracket itself. The prescription can only be realized with full engagement of the archwire into the base of the slot. With SLBs, the clinician needs to understand the system that they are utilizing in terms of when their archwires begin expressing the bracket prescription. Clinically, torque expression take time to express. A clinician that switches from one system to another must realize that the early active phase on NiTi archwires with one SLB may not translate to the same archwire with another bracket system. In this case, the clinician would observe lack of torque expression and likely blame the bracket when in reality, this issue lies with a lack of understanding in archwire progression. Ultimately, this defeats the purpose of the straight wire appliance, and the clinician must bend the archwire in order to finish the case appropriately, thereby decreasing efficiency.

4.5 Limitations of this Study

The major shortfall of this study is that the *in vitro* linear experimental testing fixture does not mimic the dynamic interactions that occur intra-orally between orthodontic brackets and archwire. Due to the intricate multitude of complexities occurring in 3-dimensions of the biological intraoral environment, this was certainly not an attempt to replicate the biological processes created by the bone/periodontal ligament/cementum interface. Rather, this study was designed to observe the classical FR between the bracket-wire interface, and as a result archwire engagement, by removing as many confounding variables as possible.

4.6 Strengths of this Study

A strength of this study was the design and fabrication of the custom-made mounting apparatus used with the Instron testing machine. Minor imperfections in mounting would have led to disproportionately greater FR values being recorded. The precise mounting of brackets and archwires allowed for the exclusion of differences in bracket prescription between systems to be realized, such that the true dissimilarities of bracket FR could be examined.

The primary strength of this study was the evaluation of a multitude of bracket systems along with a comprehensive examination of archwires. To date, there have been no published reports examining FR in this number of Passive SLB systems. The evaluation of Active SLBs with a multitude of archwires allowed for the distinct differences of engagement points to be explored between bracket systems.

4.7 Suggestions for Future Research

Future torque studies would provide insightful information that would assist in the proper evaluation of contemporary SLBs. Clinical control is improved with knowledge of when the bracket is operating in a passive and active state, as well as knowledge of when and how much torque expression is being transmitted with the appliance. Ultimately, alternative factors such as cost, durability, bond strength, patient comfort, bracket size and aesthetics as well as many other considerations are taken into account by the clinical practitioner when choosing an appliance system. All future studies that evaluate the above-mentioned factors would assist the practitioner in selecting an appliance that they can use with clinical confidence and efficiency.

Chapter 5
Conclusions

1. Passive SLBs produce significantly less FR (close to zero) than traditional twin brackets on all wire sizes, *in vitro*.
2. Passive SLBs produce similar FR to one another (close to zero) on all wire sizes, *in vitro*.
3. Active SLBs produce different FR patterns compared to traditional twin brackets on all wire sizes, *in vitro*.
4. Active SLBs produce greater FR than Passive SLBs on the two largest rectangular archwires tested, *in vitro*.
5. A distinct pattern of archwire initial engagement and FR exist for each Active SLB system, *in vitro*.

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Appendix 1

Raw Frictional Force (cN) Data for Control Brackets and Active SLBs

Bracket	n	Wire Size (NiTi)							
		0.016	0.018	.018 x .018	.020 x .020	.016 x .022	.017 x .025	.019 x .025	.021 x .025
C-Vic	1	40	48	80	83	84	99	99	83
C-Vic	2	38	76	99	74	39	88	92	87
C-Vic	3	63	73	73	90	65	111	87	94
C-Vic	4	61	59	65	96	138	126	124	113
C-Vic	5	63	34	68	83	102	99	94	125
C-Vic	6	74	94	85	72	135	117	135	98
C-Vic	7	69	86	63	72	113	92	53	113
C-Vic	8	47	72	82	48	126	125	129	99
C-Vic	9	46	41	39	88	102	106	107	101
C-Vic	10	43	42	99	79	139	99	91	97
A-Vic	1	2	1	1	1	0	54	62	56
A-Vic	2	2	1	0	1	1	42	70	68
A-Vic	3	1	1	0	0	0	72	50	70
A-Vic	4	1	1	2	0	3	81	66	65
A-Vic	5	2	1	1	0	9	52	67	60
A-Vic	6	2	1	0	1	0	78	62	49
A-Vic	7	3	1	0	0	0	37	74	64
A-Vic	8	2	1	1	0	0	78	89	63
A-Vic	9	2	0	1	1	0	63	66	72
A-Vic	10	1	1	0	2	1	37	46	63
A-Emp	1	2	1	1	42	8	55	187	203
A-Emp	2	1	0	0	4	0	78	220	216
A-Emp	3	1	2	0	4	15	92	202	146
A-Emp	4	1	1	0	80	0	70	184	227
A-Emp	5	1	2	1	18	1	85	216	220
A-Emp	6	1	0	0	52	0	95	154	190
A-Emp	7	2	1	6	42	4	102	204	127
A-Emp	8	1	0	1	99	3	107	203	168
A-Emp	9	0	1	1	69	2	83	192	167
A-Emp	10	1	1	0	32	9	89	171	183
A-Spd	1	2	0	43	45	61	71	47	73
A-Spd	2	0	24	39	47	60	65	56	80
A-Spd	3	3	0	30	62	77	46	72	79
A-Spd	4	2	1	64	64	76	74	56	72
A-Spd	5	1	29	24	54	76	67	52	59
A-Spd	6	2	1	41	51	91	81	72	66
A-Spd	7	2	0	46	65	65	68	44	84
A-Spd	8	1	1	42	38	86	78	62	76
A-Spd	9	2	6	43	34	49	69	66	45
A-Spd	10	2	19	25	42	42	54	75	57

Appendix 2

Raw Frictional Force (cN) Data for Passive SLBs

Bracket	n	Wire Size (NiTi)							
		0.016	0.018	.018 x .018	.020 x .020	.016 x .022	.017 x .025	.019 x .025	.021 x .025
P-Dmn	1							1	0
P-Dmn	2							1	0
P-Dmn	3							1	1
P-Dmn	4							0	1
P-Dmn	5							1	0
P-Dmn	6							1	0
P-Dmn	7							0	0
P-Dmn	8							1	0
P-Dmn	9							1	2
P-Dmn	10							1	0
P-Car	1							0	1
P-Car	2							1	0
P-Car	3							1	1
P-Car	4							1	1
P-Car	5							1	1
P-Car	6							1	1
P-Car	7							0	0
P-Car	8							1	0
P-Car	9							0	0
P-Car	10							0	0
P-H4	1							1	1
P-H4	2							0	0
P-H4	3							4	5
P-H4	4							1	0
P-H4	5							1	1
P-H4	6							1	0
P-H4	7							1	0
P-H4	8							6	0
P-H4	9							0	0
P-H4	10							1	0
P-Alt	1							0	0
P-Alt	2							1	3
P-Alt	3							1	3
P-Alt	4							1	1
P-Alt	5							1	0
P-Alt	6							0	0
P-Alt	7							1	0
P-Alt	8							0	1
P-Alt	9							0	0
P-Alt	10							1	1
P-Emp	1							1	0
P-Emp	2							0	0
P-Emp	3							1	0
P-Emp	4							0	0
P-Emp	5							1	0
P-Emp	6							0	1
P-Emp	7							0	1
P-Emp	8							0	1
P-Emp	9							1	1
P-Emp	10							0	0

Curriculum Vitae

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Education

2015-2018 **Western University** London, ON
MClD Schulich School of Medicine & Dentistry – Graduate Orthodontics

2007-2011 **University of Manitoba** Winnipeg, MB
DMD Faculty of Dentistry

2004-2006 **University of Ottawa** Ottawa, ON
MSc. Cellular and Molecular Medicine

2000-2004 **University of Guelph** Guelph, ON
BSc. Bio-medical Science

Research Contributions

Publications

Greene, M., Thackeray, J. et al. 2009. "Reduced in vivo phosphodiesterase-4 response to noradrenergic challenge in diet-induced obese rats". Can J Physiol Pharmacol. *87(3): 196-202.*

Kenk, M., **Greene, M.** et al. 2008. "Use of a column-switching high-performance liquid chromatography method to assess the presence of specific binding of (R)- and (S)-[^{11}C]rolipram and their labeled metabolites to the phosphodiesterase-4 enzyme in rat plasma and tissues". Nuclear Medicine and Biology. *35(4): 515-21*.

Kenk, M., **Greene, M.** et. al. 2007. "In vivo selective binding of (*R*)-[^{11}C]rolipram to phosphodiesterase-4 provides the basis for studying intracellular cAMP signaling in the myocardium and other peripheral tissues". Nuclear Medicine and Biology. *34(1):71-7*.

Scientific Meetings & Presentations

Canadian Association of Orthodontics, poster presentation (2017, Toronto)

International Association of Dental Research, poster presentation (2010, Washington)

Midwest Dental Conference, poster presentation (2010, Iowa)

Obesity NAASO Conference, oral presentation (2006, Boston)

Society of Nuclear Medicine, poster presentation (2005, Toronto)

Canadian Cardiovascular Society, poster presentation (2005, Montreal)

Canadian Federation of Biological Societies, poster presentation (2005, Guelph)

Honours and Awards

Schulich School of Medicine & Dentistry Poster Presentation Merit Award, 2017
Schulich School of Medicine & Dentistry John and Nancy Murray Prize, 2017
University of Manitoba Dean's Honours, 2007-2011
University of Manitoba Student Excellence Award, 2011
University of Manitoba Endowment Fund Award for Operative Dentistry, 2011
Sophie Kanee Memorial Prize in Dental Jurisprudence, 2011
International College of Dentists Canadian Section Student Award, 2010
Endowment Fund Award in Dentistry, 2010
Dr. FWL Hamilton Scholarship in Operative Dentistry, 2010
University of Manitoba Dean's Travel Bursary, 2010
Louis Nief Septodont of Canada Inc. Prize in Dentistry, 2010
Bronze Medal in Oral Pathology and Microbiology, 2009
Dr. William F Campbell Scholarship in Orthodontics, 2009
Dr. Jones & Katie Young Scholarship in Dentistry, 2009
RBC Scholarship for First Year Medical & Dental Students, 2007
Heart Institute Research Corporation (HIRC) Travel Award, 2006
University of Ottawa Cellular and Molecular Medicine Travel Grant, 2006
Queen Elizabeth II Graduate Scholarship in Science and Technology, 2004-2006
University of Guelph Dean's Honours List, 2001-2004
University of Guelph Entrance Award, 2000
Ontario Scholar, 2000