University of Alberta

The Effect of Perturbations on Resistance to Sliding in Second Order Moments Using Conventional Ligated Brackets Versus Passive Self Ligated Brackets

by

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Dedication

To my wife Stacy who has always been supportive in my decision to return to school. The countless hours in clinic, school and thesis have been matched with raising our beautiful children. Your dedication has allowed all this to be possible.

To Teagan and Mason. Your smiles make me want to be better. A better orthodontist, a better husband, a better father. I hope that someday you will read this and perhaps understand why dad had to go to school. I hope that one day this motivates you to be better; much like you did for me.

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Abstract

Objectives: A novel frictional and perturbation device was used to investigate the role of vibrations on resistance to sliding (RS) in conventional and passive ligated brackets

Methods: 150 3M Victory Series twins (0.022 slot) and 150 Damon Q brackets (0.022 slot) were tested using an 18 x 25 stainless steel wire for resistance to sliding. Test groups consisted of equal numbers (n=30) representing combinations of high and low amplitude and frequency of perturbations as well as control. Second order angulation tested ranged from 0 to 6 degrees.

Results: Bracket type, perturbation test condition, and interactions were all significant in affecting resistance to sliding. High Perturbations reduces RS more than low perturbations independent of frequency.

Conclusions: Passive ligated brackets have a lower resistance to sliding when compared to conventional ligated brackets under all test conditions and angulations. Amplitude of perturbations has a larger role than frequency in reduction of RS.

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List of Symbols and Abbreviations used

ANOVA – Analysis of Variance

BI – Binding

CR – Center of Resistance

F – Friction

NO –Notching

PDL – Periodontal Ligament

ANOVA –Analysis of variance

RS – Resistance to Sliding

SPSS - Statistical product and service solution

α - Alpha

β – Beta

γ - Gamma

Θ_c – Critical Contact Angle

Ɵ – Contact angle in second order (theta)

CI – Confidence Interval

Chapter 1 – Introduction and Literature Review

1.1 Statement of the Problem

The friction between brackets and wires during orthodontic tooth movement has been implicated as a factor in the efficiency in case management. Manufacturers have invested significant resources to the design of both brackets and wires in the attempt to minimize this friction. Despite novel bracket designs and new wire materials which reduce the friction in the system, clinicians are not noticing dramatic reductions in treatment times. Perturbations has been proposed as a factor that reduces the friction by unlocking the binding that occurs at the bracket wire interface when critical angles are achieved.[1] Little research has been conducted investigating the role of perturbations on resistance to sliding. To date there are no articles which attempts to quantify the effect of perturbations on the magnitude of change of resistance to sliding.

1.2 Introduction

Basic introductions to key topics in this thesis will be reviewed; this will include both the concepts of friction as it relates to orthodontics as well as resistance to sliding. For the purpose of this thesis, the orthogonal directions in all 3 planes of space for a bracket are defined by Fig 1-1. The angle Ө represents the rotation around the Y-axis which clinically translates to second order or tipping moments. The angle γ represents the rotation around the X-axis which clinically translates to third order or torsional moments. The angle β represents rotation around the Z-axis which clinically translates to first order or rotational moments.

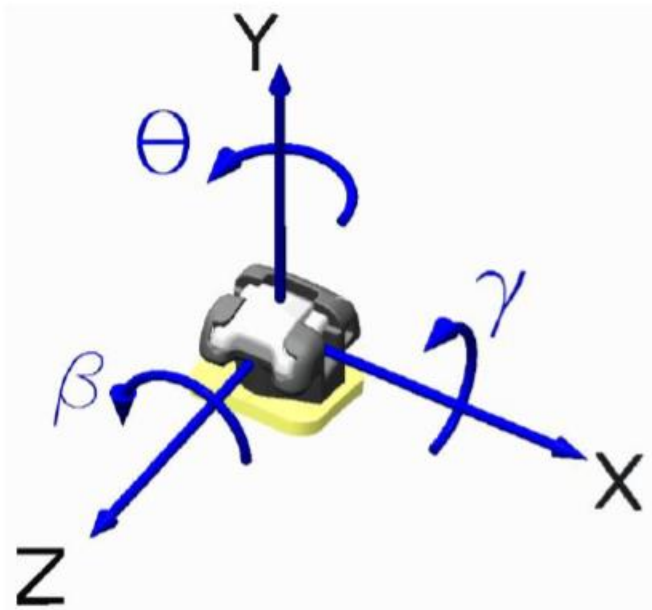

Fig 1-1. Diagramatic view of x, y, z axis orientated to bracket as well as angles Θ, γ, β.

1.2.1 Friction

During orthodontic tooth movement there is an interaction between the bracket attached to the tooth and the guiding archwire. As with any two objects that interact in this fashion, friction exists within the system. Friction has been described as "the contact resistance developed between the contacting surfaces when one of the bodies moves, or tends to move, over the other."[2]It may also be described as a force acting parallel and opposite to the direction of motion.[3] Friction can also be described by the equation:

$$F_f \leq \mu F_N$$

Where F_f is the force of friction, F_N is the normal force or the force acting perpendicular to the direction of movement, and μ is the coefficient of friction Fig 1-2.

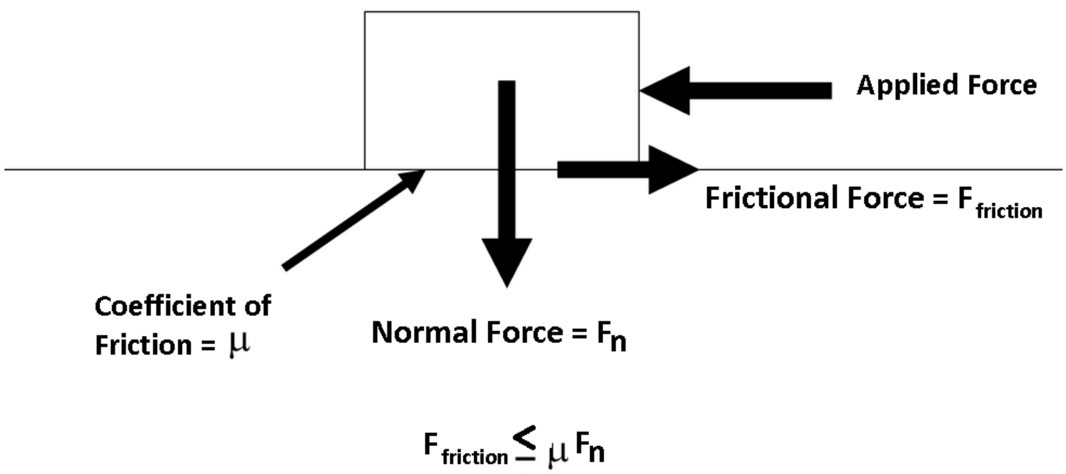

Fig 1-2. Diagrammatic representation of the equation for the force of friction.

The value for the coefficient of friction typically falls within the range of 0 and 1. Friction can also be described as being static or dynamic. Static friction is the force that resists motion between two objects that are in contact but not in relative motion. Dynamic or kinetic friction is the force of friction between two solid surfaces contacting as they slide past one another. In order for objects to slide, static friction must first be overcome. For motion to continue, force in the system must be greater than force from dynamic friction.

The force necessary to first overcome static friction is higher in magnitude than that needed to overcome dynamic friction.

Friction within an orthodontic system is a factor that must be understood by clinicians. There are certain clinical situations where it is desirable to minimize the amount of friction in order to have the most efficient tooth movement. An example where minimal friction is desired is during sliding mechanics to retract a canine into a premolar extraction space. Because the retraction force typically does not pass through the center of resistance of the tooth, teeth subjected to orthodontic retraction force tend to tip rather than translate along the archwire (Fig 1-3). As such, friction in all 3 planes must be properly understood in order to determine methods to reduce it.

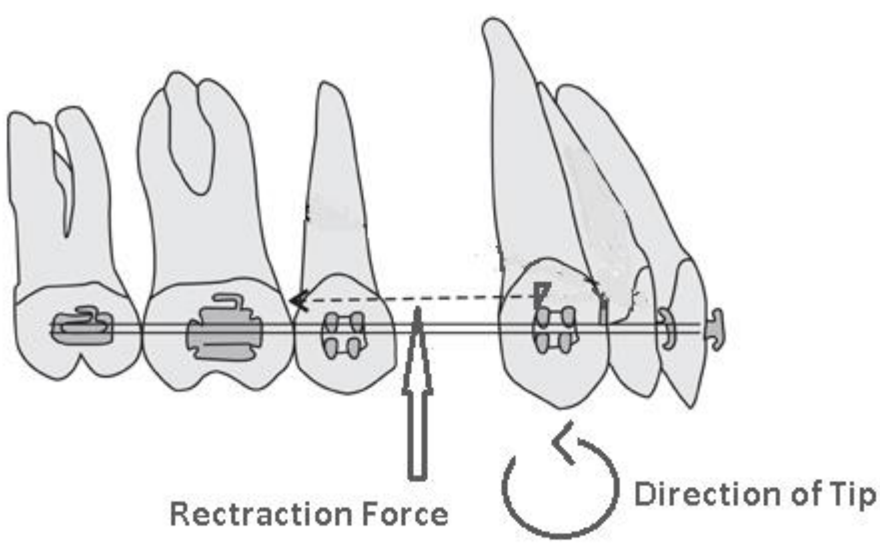

Fig 1-3. Schematic diagram of typical canine retraction into extracted premolar space on continuous archwire with retraction force from molar to canine.

Maximum friction may be useful in anchorage situations where movement of certain segments is undesirable. In general it is usually desirable to have minimal friction during the initial stages of treatment (leveling, aligning and space closure) and more friction in the latter stages of treatment (detailing). Some methods to influence friction in orthodontics are to manipulate the bracket design[4], alter materials[5], method of ligation[6], and wire size and shape[7].

1.2.2 Resistance to Sliding

Resistance to sliding is a term used in orthodontics to describe forces that oppose the movement of a bracket along the arch wire. The term friction has often been used synonymously to represent the concept of resistance to sliding.[8] Kusy describes Resistance to sliding (RS) as being composed of three components; friction (FR), Binding (BI), and Notching (NO). That is:

$$RS = FR + BI + NO$$

Friction is defined as the force acting perpendicular to two objects (normal force) times the coefficient of friction. Friction is independent of surface area. Although Kusy creates terms to describe the components of RS, the components are simply different expressions of friction and may be overly simplistic. If clearance exists between the sides of the bracket slot and the wire, then friction that is the result of the force of ligation pressing the wire against the bracket slot base dominates this equation. The friction due to ligation is composed of 2 interfaces along the y axis. The first being between ligation method and wire, and the second being between wire and bracket slot base. As the equation for friction implies, this relationship will be dependent on the materials used for ligation, wire, and bracket slot base (represented by the coefficient of friction) as well as the force that the ligature is able to apply (which represents the normal force) (Fig 1-4).

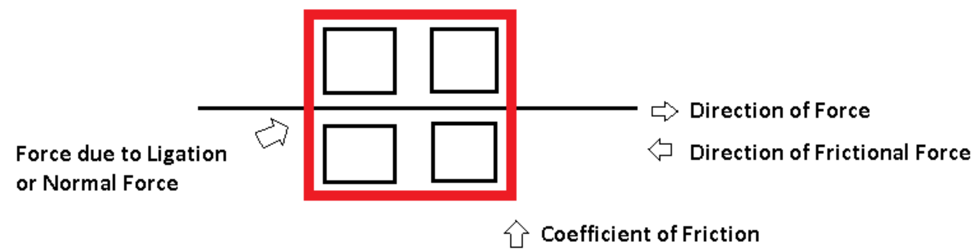

Fig 1-4. Diagram of sources of frictional force on conventional ligated bracket.

Situations may exist in treatment where the wire may be pressed against the incisal or gingival wall of the bracket creating friction in 2 planes (y and z) during sliding. This situation is more complicated as there is friction between ligation method and wire, wire and bracket slot base, as well as wire and bracket slot wall. Kusy describes these interactions as “classical friction” but does not explore the details of how and why they are occurring.[9]

As the bracket undergoes second order moments relative to the arch wire the clearance between the wire and bracket slot walls decreases and critical contact angle is achieved. The critical contact angle is angle created between the archwire and bracket slot when the wire contacts the corners of opposite walls during second order movements. This critical contact angle (Θ_c) can be calculated using the formula referenced in Appendix C. The resistance to sliding which occurs when the wire presses against the slot corners on opposite walls of the bracket slot as a result of bracket rotation is termed “binding” by Kusy.[9] Binding as defined this way is a friction resulting in the interaction of the corners of the bracket wall against the arch wire. It can still be defined as the normal force acting perpendicular to the wire/slot surface times the coefficient of friction. The difference between what Kusy refers to as classical friction and binding is the direction of the normal friction. With force due to ligation, the normal force is delivered along the y axis, however with tipping or second order movements the direction of normal force is delivered along the z-axis. Tipping of the bracket against the arch wire can result in large force magnitudes and therefore large friction forces which can play a dominant role in resistance to sliding. For example if a 1N retraction force is applied 10mm away from the center of resistance of a tooth, the tooth would be subjected to a 10Nmm moment. As the tooth tips and the wire contacts the bracket slot wall, an equal and opposite force couple is created. If for simplicity that the distance between these two forces is 2mm (width of the bracket), then a force of 5N will be felt at this wire/bracket interface. You can then calculate the force of frictional resistance by multiplying this force by the coefficient of friction. The force felt at the wire/bracket interface has the potential to be significantly larger than the initial force applied. Because the tooth does not exist purely in space, but is intermixed between bone, ligaments, vessels and other biological factors it would be difficult to precisely determine the exact moment felt at the bracket clinically. In this example the counter moment of the periodontal ligament space (PDL) and the bone have not been factored into the calculation. Typical retraction forces used in orthodontics would be in excess of 1N, and even in the presence of possible biological counter moments by the PDL and bone would likely have significant force at the wire/bracket interface. The more that $\Theta > \Theta_c$ the greater the magnitude of F_N which results in higher total friction. Factors which will influence this form of friction would include material of wire, material of bracket slot wall and bracket design such as beveled edges. Kusy refers to "binding" as a result of second order angulation (rotation around the y axis). Similar interaction may occur in the situation of a rotated tooth where friction occurs between wire and edge of the bracket slot base or bracket gate (in the case of passive ligated brackets) when there is rotation around the z axis. As the concept is the same, it is more accurate to describe this form of friction by contacting surfaces and direction of force in 3 dimensions.

Notching occurs when there is deformation of the wire and or bracket surface resulting in mechanical interlocking to prevent sliding. Factors which influence notching are wire material, bracket slot material, and bracket and wire geometry. Harder wire materials such as stainless steel are less likely to develop notching when compared to softer materials such as beta titanium. In terms of bracket material, metal brackets are less likely to create notching in wires when compared to harder materials such as ceramics. Rounded bevels on both wires and bracket edges are better able to dissipate the forces which should reduce the effect of notching.

Kusy suggests that the largest influence in resistance to sliding when critical contact angle is exceeded comes from “binding” and “notching.”[1] This may be true if there is no friction from third order angulation (rotation around the x-axis) and the wire is parallel to the bracket slot. Most orthodontic brackets have a bracket depth of 0.025 inches which is equivalent to 0.64 millimeters. If the average width of a bracket is roughly 2mm and the friction associated with second order moments dominate resistance to slide when critical contact angle is exceeded, then frictional resistance when third order moments are present have even more potential to influence resistance to sliding. Because depth is so small, stiffness of the wire increases and the critical contact angle along the y axis decreases. Wire geometry would be an influence in this plane as only dimensional wire would be capable of creating a couple. Kusy does not consider friction in this plane and this scenario is used to further illustrate that previous accepted methods of describing resistance to sliding may be overly simplistic.

1.2.3 Critical Contact Angle

The critical contact angle (Θ_c) has been referred to as the point where there is a shift in influence on resistance to sliding from friction due to ligation to binding factors.[1] It can be defined by the equation in Appendix C if dimensions are known for the bracket slot and archwire. When $\Theta < \Theta_c$ this has been termed the passive component where friction due to ligation method dominates RS. $\Theta = \Theta_c$ occurs when the archwire makes contact on opposite sides of the slot corners of the bracket. This is the point where binding begins to be more influential in RS and is referred to as the active component. As $\Theta > \Theta_c$ binding plays a larger and larger role until notching occurs when sliding ceases.[10] Factors which can influence Θ_c include bracket width, slot size, and wire size (Fig 1-5).

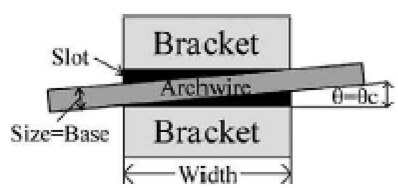

Fig 1-5. Diagram of bracket-wire interaction and the critical contact angle[4]

1.3 Significance of the Study

Resistance to sliding has been a topic that has been extensively investigated within the orthodontic literature. Rarely in clinical situations does a tooth move where the wire stays perfectly parallel in the bracket slot. What typically happens is that tipping moments are felt so that binding and notching may play a significant factor in resistance to sliding. Only recently have we seen research on resistance to sliding incorporate perturbations into the study design. It has been postulated that vibrations or perturbations may influence the resistance to sliding by temporarily "releasing" the friction associated with binding and notching. As $\Theta \geq \Theta_c$ the dominant factor in resistance to sliding is the friction associated with binding and notching, so significant reductions in resistance to sliding may be realized through the presence of perturbations. Although there are a limited number of studies that did explore the effect of perturbations on resistance to sliding, none were able to accurately quantify the change. Using a novel perturbation device along with a 3D frictional device, we will be able to not only report the effect but to also quantify any changes in resistance to sliding as a result of the perturbations.

1.4 Research Question

Do perturbations change the resistance to sliding during second order moments?

Is there a difference in resistance to sliding for conventional compared to passive ligated systems in the presence of perturbations?

What is the effect of frequency and amplitude of the perturbations on resistance to sliding during second order moments?

1.5 Hypothesis

This study tested the role of perturbations on resistance to sliding using both conventional and passive ligated brackets. The null hypotheses are as follows:

Ho : There is no difference in resistance to sliding between perturbation groups and control groups for conventional brackets at 0 degrees of bracket rotation around the y-axis.

Ho : There is no difference in resistance to sliding between perturbation groups and control groups for conventional brackets at 6 degrees of bracket rotation around the y –axis.

Ho : There is no difference in resistance to sliding between perturbation groups and control groups for passive ligated brackets at 0 degrees of bracket rotation around the y-axis.

Ho : There is no difference in resistance to sliding between perturbation groups and control groups for passive ligated brackets at 6 degrees of bracket rotation around the y-axis.

Ho : There is no difference in resistance to sliding between conventional and passive ligated brackets under any test condition at 0 degrees of bracket rotation around the y-axis.

Ho : There is no difference in resistance to sliding between conventional and passive ligated brackets under any test condition at 6 degrees of bracket rotation around the y-axis.

1.6 Literature Review

1.6.1 Conventional and Passive Ligated Brackets

Historically orthodontic wires had to be secured to the brackets using some form of ligature. Ligature materials whether steel or elastomeric contribute to the friction between the bracket base and the wire as well as between the wire and the ligation material.[11-13] This type of bracket has been referred to as conventional ligated brackets. Passive self ligated brackets are designed with a locking door forming a tube around the wire. This avoids the friction resulting from the normal force of the ligation material pressing the wire against the base of the bracket. By removing this source of friction, passive self ligated brackets are thought to facilitate sliding movement of the wire through the bracket slot.

Recent popularity of the passive ligated bracket in the orthodontic community has come from the demands for less friction in the system. Some clinicians have equated less friction with quicker and more efficient treatment.

Experimental studies to test whether friction is lower in conventional compared to passive ligated brackets has been highly criticized and debated. Several articles cite that passive or self ligated brackets show lower frictional force when compared to the conventional ligated bracket.[7, 13-16] The only systematic review published on frictional resistance between these two types of brackets suggest that passive ligated brackets have lower friction only when round wires are used in relatively well aligned arches and when no tipping and torqueing forces are present.[8] There is insufficient evidence at the time of publishing to determine that passive ligated brackets have lower frictional resistance in the presence of larger dimensional wires, more malposition within the arches or more significant tipping or torqueing forces.[8] The combinations between all the different bracket, wire and ligation materials available on the market today produce an almost infinite number of combinations. This combined with different methodology and testing apparatus has produced a number of articles where definitive comparisons and conclusions are virtually impossible.

1.6.2 Perturbations

Teeth that move as a result of orthodontic force tend not to move smoothly sliding along the archwire as one may expect. Pure translation can only occur if the force of movement passes through the center of resistance (CR) of tooth.[1] Due to the fact that orthodontic brackets are placed at some distance away from CR and that forces are usually applied to the bracket, pure translation is often not clinically possible. Orthodontic tooth movement has been described by some as a sequence of tipping movements, biological responses, uprighting and bone remodeling, followed by more tipping.[17, 18] Others have described this movement as a stick-slip behavior.[19]

The majority of orthodontic literature has placed the interaction between the bracket wire interface to be the most influential factor in friction.[17] Perturbations have been postulated as a factor that may influence orthodontic tooth movement. The thought is that the vibrations temporarily reduce the effect of binding and notching at the wire-bracket contact thus allowing for more efficient orthodontic movement.[20] This being said, the majority of published research on friction and resistance to sliding have been conducted using a steady state model. Limited number of studies have been conducted which involve perturbations; these studies will now be reviewed individually.

Braun et al. investigated the role of perturbations on frictional resistance using various bracket, wire and ligation combinations. Both wires and brackets tested were composed of stainless steel. Three archwires were tested (0.018 x 0.025, 0.016, and 0.016 x 0.016) with a standard 0.018 twin bracket for a canine and a premolar. Brackets were mounted to jigs to both allow for tipping movements of the bracket as well as to simulate a center of rotation of 10mm to simulate uncontrolled tipping movements. Bracket angulations tested ranged from 0 to 25.5 degrees. Brackets were secured to wires using 0.010 steel or elastomeric ligatures. Random frequency and direction of perturbations was created by measured finger pressure to the wire or bracket in all 3 planes of space as to simulate the oral environment. All perturbations were applied by the same person and the force applied was measured using a Correx

(Haag-Streit, Koeniz, Switzerland) tension gauge. Mean force applied was 0.86N (range 0.20 to 1.96N). The wire was pulled at a rate of 0.1mm/min and the frictional resistance measured using an Instron tension testing machine. The author found that there was a momentary reduction in frictional resistance to zero in 95.8% of the experiments conducted regardless of bracket size, wire size or dimension, or ligation method. The author acknowledged that the sample size was small (total n=47) for the number of test groups used in this study. This group also identified that the rate of pull was significantly faster than rate of wire slide during orthodontic movements (1mm/month). Evaluation of the graphs in this article suggest that although frictional resistance momentarily reduces in the presence of perturbations, there appears to be significant variability of frictional resistance between samples. This suggests that there may be reliability issues with the testing methodology used in this study. It is also noted that although maximal tested angulation (25 degrees) far exceeds that of critical contact angle, notching did not seem to be achieved as the wire continued to be pulled through the bracket slot. [21]

Liew et al. studied the frictional resistance between a single bracket and stainless steel archwire that was subjected to displacements. Only a single wire type (0.016 x 0.022 stainless steel) and bracket type (0.018 x 0.025 conventional ligated) using elastomeric ligature was used for this experiment. The wire was pulled using variable weights off a low friction pulley. Displacements were created on the top of the wire along the z-axis with forces ranging from 0.25N to 4.41N at a frequency of 91 cycles per minute. There was no indication in the article as to the reason the tested frequency of 91 cycles/min was selected. The minimum force required to produce arch wire sliding through the bracket slot was used to assess the frictional resistance. Forces applied that were below this minimum level did not allow sliding between the wire and bracket. If perturbations reduce frictional resistance, then sliding should occur at levels below this minimum force in the presence of vibrations. The experiment consisted of testing different levels of perturbations against fractions of the minimum force to measure the rate of wire slide. A major criticism of this article is that it does not include sample size, group assignments, or the statistics used to derive the conclusions. This group concluded that resistance to sliding may be decreased by up to 85% with displacements along the z-axis. The author reports that maximum reduction in frictional resistance occurs with vertical displacements resulting from forces between 0.98N and 2.45N grams. The study shows that loads beyond this optimum range result in decrease in wire movement suggesting that frictional resistance once again is increased. The author provides no explanation as to why loads greater than 1.47N resulted in frictional resistance that were similar to those under conditions without perturbations. The low friction pulley used in this experiment may introduce a potential confounding factor in that it is another source of friction in the system. Friction from the pulley in the publication was not reported suggesting that it was either nominal or not accounted for. It is worth noting that although frictional resistance was reported, this variable was not directly measured and only inferred indirectly from the rate of sliding. This study also did not investigate the influence perturbations on friction between the arch wire and the walls of the bracket slot when second order angulations are introduced as wires were only pulled parallel to the direction of the bracket slot.[20]

Clocheret et al. conducted a pilot project published in 2001 and continued with a more extensive experiment which was published in 2004. This group investigated the frictional behavior of bracket and wire combinations subject to small oscillating displacements. 15 different arch wires of various materials were used in this study. The 3 different Nickel-Titanium (NiTi) wires were 0.016 x 0.022 and the remaining 12 composed of other materials and brands(stainless steel and beta titanium) were 0.017 x 0.025 in dimension. 16 conventional ligated brackets were selected of various materials (plastic, ceramic and stainless steel) all with a slot size of 0.018 x 0.025. This group designed a novel MTM fretting apparatus that has an x,y,z positioning system that is able to deliver a fixed frequency and amplitude of displacements. This device is capable of recording the kinetic coefficient of friction and the frictional force. The device was able to apply a 20N force against the wire to push the wire against the bracket slot base similarly to, but more uniformly than, ligatures; thus ligatures were not needed for this experiment.

It is not clear in the article as to what plane (x,y or z) that displacements were delivered nor the actual amplitude of force delivered. The author only references that oscillating lateral displacements of 200 µm were delivered at a frequency of 1 Hz. It is also not clear from the article or the diagram of the device where the perturbations were being delivered (ie at the bracket or at the wire). It is also not clear as to rationale why the frequency of 1 Hz was selected. Wires were pulled parallel to the bracket slot and no second order angulations were introduced in this experiment. This group measured the coefficient of friction which is a value unique to each different wire-bracket combination. The use of perturbations in this study was an attempt to create a dynamic environment similar to the mouth. The purpose of this study was to gather coefficient of friction data on various bracket-wire combinations so that clinicians may better select the right set for the desired clinical purpose. The criticism of this article is that although the title describes the term behavior and is written up as an experiment, it lacks may elements of a true experiment (eg experimental and control groups) and seems to be merely a report of observations.[22, 23]

Sirisaowaluk et al. investigated the effect of different types of ligation on resistance to sliding. This group used 3 lower incisor stainless steel twin brackets (0.018 slot) with 0 degree tip/torque/or rotation. The 3 brackets were mounted in series with a distance of 14mm and 7mm in between the brackets respectively. No second order movements were introduced in this experiment as brackets were mounted in parallel. 8 different types of ligation (elastomeric and steel both tied in different patterns) were tested using a straight length of 0.016 x 0.022 stainless steel wire. Individual ligation test groups had separate brackets, and tests were repeated 8 times with wires and ligation being replaced on each test. Although not reported, total sample can be interpreted as being 64. Repeated measures sampling (8 tests) was done on the 8 individual test conditions. This group used a similar method as Liew et al. in that they measured the minimum force to overcome friction and then measured rate of wire travel per unit of time (mm/min). The author reports that repeated vertical displacements were administered at load of 0.49N and a frequency of 91 cycles/minute, however no mention as to what plane (x,y, or z) these perturbations were delivered. Linear measurements were made over an 8 minute test in millimeters using a ruler and later converted to micrometers. In respect to perturbations, they found that in 7 of the 8 methods of ligation there was a reduction in static friction when vertical loads were introduced. There was no quantification of the magnitude of reduction in friction in the presence of perturbation. This conclusion was based on the observation that the wire at a force below the minimum amount required to initiate sliding began to slide in the presence of perturbations. As with the previous study, friction from the pulley was either nominal or again not accounted for in this experiment. The author recognizes that sample size is small and straight well aligned testing conditions used. They conclude that further research is needed to verify results.[24]

O'Reilly et al. studied the effect of displacements on the resistance to sliding. 320 brackets were examined in 16 different test groups (n=20 per group). Conventional twin brackets were modified by the manufacturer to have strips of stainless steel welded over each pair of wings to eliminate the need for ligatures. This converted the bracket from a conventional ligated bracket to more of a tube or passive ligated bracket. All tested brackets had a slot size of 0.022 x 0.028. 4 different wire types were tested which include: 0.019 x 0.025 stainless steel, 0.019 x 0.025 beta titanium, 0.021 x 0.025 stainless steel and a 0.016 stainless steel. Teeth when retracted by orthodontic force tend to tip and upright against the wire as opposed to purely translating along the wire. To simulate this type of retraction, a counter weight (100grams) was applied to cause rotation of the bracket along the y-axis thus introducing second order moments. Perturbations were created by a vibrating machine and delivered 10cm away from the test bracket. Although not formally stated in the article, it appears that the perturbations result in the bracket rotating around the y-axis. Frequency and amplitude was set using an electromagnetic functional generator. For this experiment, the frequency of 1.35 Hz (81 cycles/min) was selected. Amplitude was derived from results from a pilot study which suggested that a substantial change in sliding resistance (the degree of change was not reported) occurred with displacements between 0-1mm. Based on pilot results amplitudes of 0, 0.25mm, 0.5mm and 1mm were selected for the final experiment. In the discussion section the group suggests that these displacements 10mm away from the bracket would result in displacements of 0, 0.04, 0.08, and 0.16mm at the level of the bracket. A total of 16 test groups were created consisting of the 4 wire types and the 4 amplitudes each containing 20 samples. The speed at which the wire was pulled during the experiment was 1mm/min. This group concluded that resistance to sliding between brackets and arch wires is significantly reduced with the introduction of repeated displacements. The amount of reduction was also dependent on the size and material of the arch wires. No perturbation or control group showed that beta titanium wires had the most friction followed by larger dimensional stainless steel with round stainless steel having the least friction. Statistically significant (α=0.05) reductions in sliding resistance was seen in all displacement groups for 0.021 x 0.025 stainless steel, whereas significant reductions only occurred at 0.5mm or higher for the 0.019 x 0.025 and 0.016 stainless steel. 1mm displacements were needed to statistically reduce the sliding resistance for the beta titanium wire tested. The group concludes that there is an 85% reduction in sliding resistance for 0.021 x 0.025 stainless steel, 80% for 0.019 x 0.025 stainless steel, 27% for 0.019 x 0.025 beta titanium and 19% for 0.016 stainless steel over the range of displacements tested. A criticism of this experiment is that this group chose to measure amplitude of perturbations in millimeters of displacement of the test wire. There is no mention as to the amount of force needed to generate the displacements nor the fact that the forces would be different with the different materials and geometries of the wires. The final statement by this group suggests that the importance of true friction may be less than what was once predicted due to in vivo bracket and/or arch wire displacements.[25]

Most recently Olsen et al. studied the effect of vibrations on "stick-slip" behavior exhibited during second order orthodontic movements when using sliding mechanics. This experiment consisted of 2 separate parts. The first part involved determining the amplitude and frequency to be tested. 6 subjects were to incise a predetermined size of raw carrot and maximum frequency (Hz) and peak to peak amplitude (mV) was measured at the maxillary right canine using an oscilloscope. This group converted peak to peak amplitude to millimeters with the conversion of 50mV = 0.08mm. Details regarding how this conversion was determined were not included in this paper. The group also recorded a single impulsive event (biting a carrot) and using the period of this event determined parameters for a cyclic disturbance that was used in the second phase of their experiment. Initial concerns with this methodology is the ability to standardize the carrot sample as well as the small sample size with only limited number of tests per sample (5 tests). Mean vibrational frequency was 98+/-41 Hz with what seems to be a large range between 58 to 139Hz. Mean peak to peak amplitude is reported to be 151+/-39 mV with another large range between 112 and 190 mV. This group chose to set the range as being mean +/- 1 standard deviation. These values were used to establish the test protocols and experimental conditions in the second part of the study. The major criticism of this preliminary study is that the amplitude varies from 112 to 190mV which converts to 0.18mm to 0.304mm. The average periodontal ligament (PDL) space ranges in width from 0.15 to 0.38mm.[26] It would seem at first glance that this range fits nicely with physiological tolerances, but without reference as to how the mV conversion to mm was derived it is difficult to accept that this range of displacement is accurate.[19]

The second portion of the experiment by Olson et al. examined the role of vibrations on what they describe as stick-slip behavior using both conventional and passive ligated brackets. Total sample size tested was 90 distributed among 9 test vibrational groups (each group n=5). 45 conventional ligated twin brackets and 45 passive ligated brackets were used in this experiment. Friction was assessed in this study indirectly through analysis of time dependent changes in bracket position. Distance was determined through video capture of brackets along a ruler (in mm) assessed by 3 evaluators. There was no clear indication in the article as to how time was measured. The perturbations were created by an impulse hammer that was secured to the diaphragm of a speaker. The speaker was wired to a waveform generator used to create and control the level of perturbations. As the diaphragm vibrated, this would also cause the hammer to vibrate making contact with the test wire at some distance which was not reported from the test bracket. Perturbations from evaluation of the diagram seem to be along the z-axis but direction was not formally reported. A 0.032 stainless steel wire that attached to the bracket but extended 10mm above created a moment arm. A nickel titanium closing coil with a reported force of 150N was used as the retraction force. Frequencies tested in this experiment were 60, 100 and 140Hz. Amplitudes tested in this experiment were 110 (0.12mm), 150 (0.16mm) and 190mV (0.20mm). The same concern as from the initial experiment as to how the conversion between mV and mm was derived. Even with the groups non referenced conversion of 50mV = 0.08mm these values are incorrect. 110, 150, and 190mV would correspond to 0.18, 0.24, and 0.30mm respectively if that is in fact the conversion used. This group concluded that there is no statistically significant change in rate of bracket movement (which they infer is representative of frictional resistance) as a result of manipulation of frequency of perturbations. They also concluded that changes in the level of displacement does cause statistically significant changes in rate of bracket movement especially at the medium and high levels that were tested. The findings of this study must be interpreted with caution due to several criticisms. 33 of the total 90 trials, which accounts for over one-third of samples had brackets that failed to slide after activation under test conditions. These tests that did not slide were arbitrarily assigned a maximum value of 900 seconds creating a significant number of potential outliers in the data set. No clear explanation of why such a significant number in all test groups had this issue. Because the source of the perturbation is distant from the bracket, initially desired levels of displacement may not be completely expressed at the bracket level due to loss of energy. It is reasonable to assume that because of the distance, the amount of displacement would be less at the bracket level and would likely get smaller as the bracket is further retracted away from the source of perturbation. Elastomerics used for the conventional ligated brackets were prestretched to 3 times the original lumen size to simulate intraoral decay. There is no justification as to why this value for stretching was chosen, nor comments on how this would affect the frictional resistance from ligation method. Although the concept of the study most certainly is promising, flaws in methodology and assumptions made during early stages make it difficult to accept the conclusions made in this experiment.[19]

1.6.3 Second Order Movements

Second order movements are a consequence of applying a force away from the center of resistance causing the tooth and bracket to tip onto the guiding arch wire. The amount of tip produces an important angle between the arch wire and the edges of the bracket slot referred to as the contact angle (Θ). As previously stated, when the archwire contacts the opposite corners of the bracket slot the critical contact angle is achieved ($\Theta = \Theta_c$).

Several experiments have been conducted in an attempt at determining the influence of second order movements on frictional resistance.[4, 7, 10, 27] General conclusions that can be made from these studies suggest that factors which influence the effect of second order movements include slot size, bracket width, arch wire size, and design of bracket walls as all these can alter the critical contact angle. Due to the vast number of bracket wire combinations and that methodology often is different between studies; it is prudent not to overgeneralize reported results.

1.7 Conclusions

There is continued debate within the orthodontic community as to the difference in efficacy between conventional and passive ligated brackets. Friction within the system seems to be a commonly used topic to spur on this debate. Although perturbations have been postulated as a possible mechanism for reduction in friction, it has not been extensively explored. Several of the studies that investigate the role of perturbations test sliding only along the x-axis with no considerations of movements in other planes (y or z axis).[20, 22, 24] Braun et al was the only group to test the role second order moments in their experiment.[21] Both O'Reilly and Olson et al incorporated tipping movements, but these second order moments were not a test variable.[19, 25] In the clinical setting, brackets are rarely aligned perfectly parallel to each other. As such second order moments are often involved in the force system. Because friction associated with second order moments is magnitudes larger compared to friction from ligation, it is important to investigate the role of perturbations on this potentially more significant source of friction. Frictional resistance to sliding in all previous studies was either inferred through measuring other variables, or measured at the wire and not the bracket. The limited data that exists today can be further examined using more advanced technology and improved methodology. As a result, there is scientific value to conduct this experiment testing the role of perturbations using the novel 3D frictional device to further understand the role of perturbation in resistance to sliding

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Chapter 2 – Maximum Bite Force During Mastication – A Systematic Review

2.1 Introduction

The force systems associated with orthodontic tooth movement have historically been studied in two dimensions. Three dimensional orthodontic force measurements have just been recently evaluated on a high canine model comparing passive ligated brackets vs. conventional ligation.[1] In this article it was concluded that "the passive self-ligated method produced a more accurate force system for this malocclusion, with fewer unwanted forces and moments compared with elastic conventional ligation." They also concluded that "[they] would expect to see more vertical canine movement and less tipping of the adjacent teeth with passive ligation compared with conventional ligation." Amongst orthodontic practitioners there is some criticism of the conclusions as to why they do not see these results consistently in clinical practice.

One possible explanation to this question is that the in vitro results do not adequately represent the in vivo system. There is often debate in the clinical world as to the ability to translate in vitro results to the in vivo population.[2, 3] There tends to be little research that compares in vitro vs. in vivo results as it relates directly to the field of orthodontics.[4] The complexity of the oral environment and the inability to adequately reproduce the in vivo system are likely important factors.[3]

From all the variables that interact during tooth movement a possible significant factor may be the role of perturbations on the frictional system. Perturbations are defined as "a disturbance of motion, course, arrangement, or state of equilibrium."[19] In the mouth, perturbations can be generated by occlusal forces generated during mastication. These perturbations may be involved in releasing binding at the bracket slot/archwire interface during active orthodontic tooth movement.[5]

In order to better relate the in vitro findings to in vivo conditions, it is important to investigate the current understanding of masticatory forces. Many factors are important in mastication including intensity, frequency and duration. The purpose of this systematic review is to gather and organize the available scientific literature on masticatory intensity. In the future our research group will investigate the role of perturbations on the 3D orthodontic force system.

2.2 Methods

An electronic search of the literature was completed using the following databases: PUBMED (1950 to present), EMBASE (1980 to present), and SCOPUS (1996 to present). The search terms and their combinations were selected and used with the assistance of a health sciences senior librarian (Table 2-1 and Appendix A).

Search Terms	Results
1. masticat* OR chew* OR bite OR biting OR mastication MeSH	60175
2. frequen* OR frequency OR intensity OR force OR pressure OR strength OR duration OR interval OR period	4515965
3. denture* OR removable OR edentulous OR missing teeth OR implant* OR partial* OR explode "dentures"/ MeSH all subheadings	728981
4. brace* OR orthodont* OR explode "orthodontics"/MeSH all subheadings	62018
5. 1 AND 2 NOT 3	1141
6. 5 AND 4 Limit Human, English	1014

Table 2-1. Search strategy for PUBMED

Inclusion criteria for the selection of articles based on their abstracts/titles from the above mentioned databases were:

- quantitative results
- only human subjects
- evaluation of tooth borne occlusion
- mixed or permanent dentition
- articles in English.

Human subjects was considered as an inclusion criteria to eliminate all articles that were *in vitro* so that the present conclusions could better relate to real clinical conditions. The typical orthodontic patient who is ready for treatment usually presents with mixed or permanent dentition as well as tooth borne occlusion.

First round of screening consisted of reading the title and abstracts from all articles identified from each database as identified by the above search criteria. This initial level of screening was conducted by two independent researchers (Dr Wong and Dr Major). All articles that appear to match the inclusion criteria were selected independently and results were compared. Articles that matched between the investigators were accepted into the next selection phase. Articles that did not include an abstract but seemed to meet inclusion criteria were included at this phase. Discrepancies were settled by discussion.

The second phase of the search involved obtaining the full text of all articles selected in the first phase. All articles were again reviewed independently by the same two investigators. The same set of inclusion criteria utilized in the first phase of the search was applied to the second phase. Results were compared and articles that both researchers agree met inclusion criteria were selected for inclusion in the systematic review. Disagreement was resolved by debate as to whether include or exclude the paper.

The final step was hand searching the reference lists of the selected articles for any additional papers that were not initially identified through the electronic search. Articles deemed relevant were retrieved and subject to independent review by the same two investigators.

The principle outcome variable for this systematic review was to identify a quantifiable mean for maximum bite force with respective standard deviations. An emphasis was also put in identifying co-variables that affect the intensity of the mastication force.

2.3 Results

From the initial 1014 articles that were reviewed, 11 articles were finally included in the final draft as outlined in Fig 2-1.

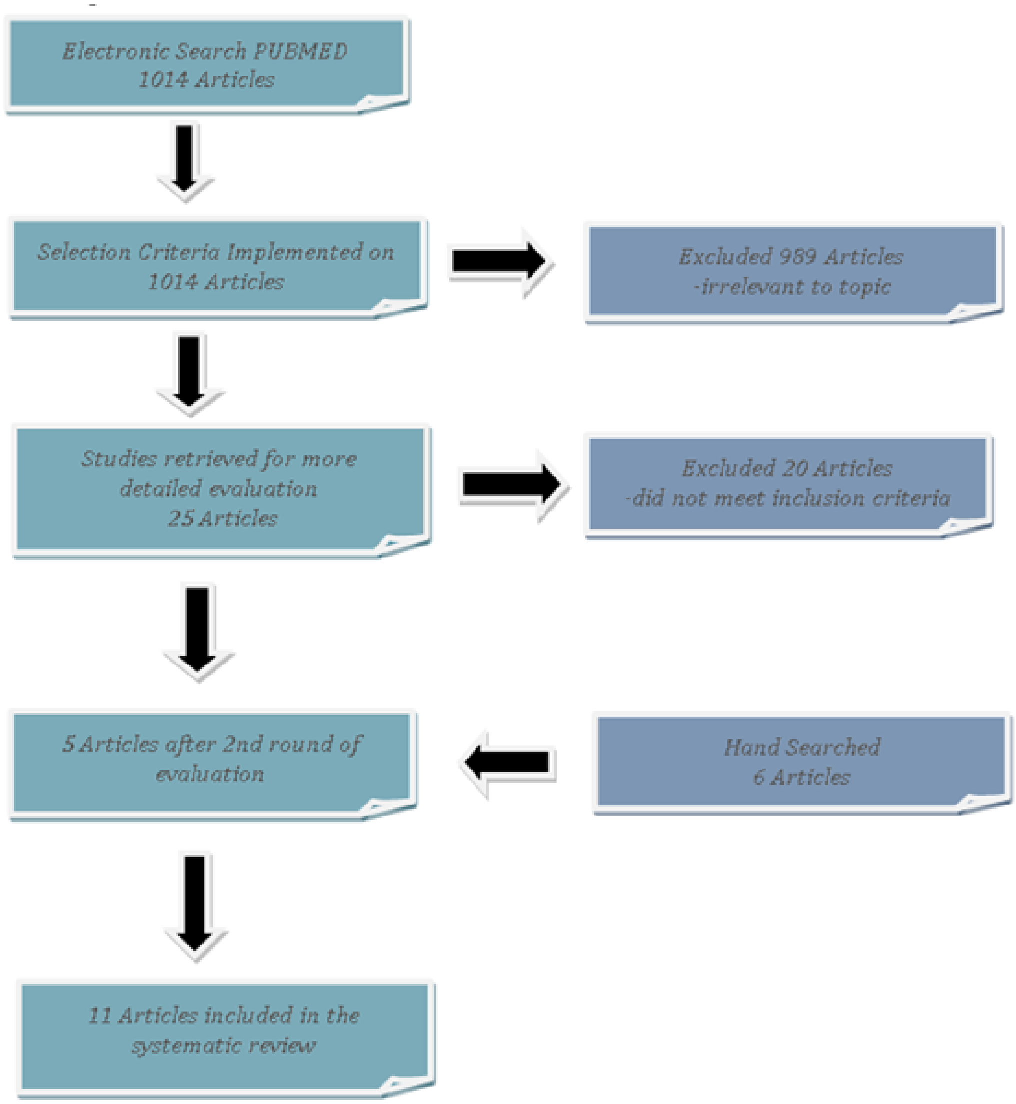

Fig 2-1. Flow diagram of search process

A summary of key findings of the articles selected are presented in Table 2-2.

Author	Sample	Method of Measure	Results	Conclusions
Kamegai *et al.* (2005)	Age: 3-17 years N=2594 (1248 Males, 1346 Females)	Occlusal force gauge placed bilaterally on first molars in mixed and permanent dentition and primary second molars in primary dentition	Age 3-5 years mean bite force 186.2 +/- 96.3 N males and 203.4 +/- 97 N in females Age 15-17 years mean bite force 545.3 +/- 182.8 N in males and 395.2 +/- 162.5 N in females	Bite force tends to increase with age in both males and females. Males tend to have higher bite forces than females. Bite force is related to occlusion.
Usui *et al.* (2007)	Age : average 8.6 in youngest group and 25 for oldest group N=350 (150 Males, 200 Females)	Simplified digital occlusal force meter on occlusal surface of maxillary first molars. Results repeated 100 times per subject.	Avg age 8.6 years mean bite force 26.2 kgf (256.9N) in males and 20.9 kgf (205N) in females Avg age 25 years mean bite force 51.6 kgf (506N) in males and 40.7 kgf (399.1N) in females	Maximum occlusal force increases from childhood until 20's. Males tend to have higher force values compared to females. Negative relationship between mandibular plane angle and max occlusal bite force
Raadsheer *et al.* (1999)	Age: 18-36 years N=121 (58 Males, 63 Females)	Bite force transducer built into biteplate that spans maxillary first molars and incisal edges of	Mean maximal bite force of 383.6 +/- 86.2N for females and 545.7 +/- 115.1N for	Males tend to have higher bite forces compared to females possibly due to difference in

		maxillary central incisors and is centered on mandibular canine. At least 1 minute duration per test	males	masticatory musculature. Direction and size of masseter and anterior digastric muscles most influential in maximum bite force
Sonnesen L, Bakke M (2005)	Age: 7-13 years N=88 (40 Males, 48 Females)	Minature pressure transducer bilaterally at the first mandibular molars for 1-2 seconds of maximum clenching. 4 trials per side with 2-3 minute rest intervals.	Mean bite force 370.4 +/- 64.8N for males and 355.3 +/- 78.7N for females	Bite force increased with age. Gender difference may be explained by different growth intensity in the groups.
Kiliaridis S *et al.* (1993)	Age : 7-24 years N=136 (79 Males, 57 Females)	Bite force recorder at 3 locations (bilaterally at molars and between incisors)	Range of maximum bite force at molars Males: 470+/-98N to 807+/-140N Females: 472+/-82N to 650+/-196N Range of maximum bite force at incisors Males: 116+/-58N to 224+/-60N Females: 111+/-48N to 223+/-57N	Bite force increases with age. No differences were noted in bite force between sexes except in adults were males tend to be higher.
Braun *et al.* (1995)	Age: 26-41 years N=142 (86 Males, 56 Females)	Pressure sensitive transducer placed across the arch in the maxillary first	Mean bite force in males was 814+/-209N in males and 615+/-209N in	Males tend to have larger bite forces than females. Age did not correlate well

		molar and second premolar area. Each measurement was done 3 times with 2-3 seconds inbetween. Reliability done with 25 randomly selected subjects 24 hours later showed correlation of 0.89 between the 2 tests.	females.	with bite force (suspect due to the fact that all subjects were adults)
Braun *et al.* (1996)	Age: 6-20 years N=457 (231 Males, 226 Females)	Bite force transducer positioned across the arches in the maxillary deciduous first molar or first premolar region. 3 times per subject resting 2-5 seconds between bites.	Maximum bite force varies from 85N - 175N depending on age	Bite force increases with age independent of gender. Lower bite forces were obtained because test area was in the premolar area compared to other studies which used the molar region.
Hatch J.P *et al.* (2000)	Age: 37-80 years N=631 (283 Males, 348 Females)	Cross arch force transducer at the first molar area. Single measurement generated using a cross arch splint. 3 highest of 10 trials used.	Mean bite force was 583.49+/-281.11N	Number of functional teeth in the posterior was important factor in bite force.
Julien K.C *et al.* (1996)	Age: 6-35 years N=45 (15 Males, 30 Females) Note: only	Dual beam transducer. No mention of location or duration or number to trials	Maximum bite force in: Adult males 596.7+/-125.4N Adult females	Difference in force between males and females may be related to muscle

	females were used in the 6-8 age group		451.3+/-130.4N Young girls 406.1+/-90.3N	differences. Further exploration into what potential differences were not reported
Proffit W.R *et al.* (1983)	Age: Mean age of control 26.9 +/- 4.4 years, long face 22.7 +/-4.9 years. N=40 (15 Males, 25 Females)	Thin force piezo-electric transducer placed on the distobuccal cusp of the lower first molar. Quartz transducer placed 2.5mm anterior to previous.	Maximum bite force in normal group was 320+/-184N and 152.8+/-103.5N for long face group	Difference in force of occlusion between normal and long faced adults. There was no further breakdown to evaluate differences between males and females
Proffit W.R, Fields H. W (1983)	Age: 6-11 Years N=30 (14 Males, 16 Females)	Piezo-foil transducer and quartz transducer placed on the distobuccal cusp of lower first molar either left or right.	Maximum bite force in normal group was 152.8+/-139.1N and 120.1+/-101.2N in long face group	Children have bite force about half or normal adults. Difference in force between normal and long faced children. No further investigation regarding differences in sex

Table 2-2. Summary of key findings from selected articles (n=11)

All selected articles were observational in design. Methodology between studies was also different so that direct comparison of the results between studies would need to be taken with caution. Differences in methodology include the testing device that was used, the location that the testing device was placed intra orally, the age groups, and the distinction between males and females. No internal reliability tests were done to verify test results except by Braun, who reported a reliability value of 0.89.[8]

2.4 Discussion

At the time of writing, there was no systematic review regarding magnitude of bite force and relationship to age, gender, tooth position on the dental arch or craniofacial morphology. The method of measurement greatly varied amongst the investigators which prevented a Meta analysis. Even with the difference in measuring equipment and protocols, there are concepts that seem to be in agreement.

The majority of the studies demonstrated that maximum bite force increases with age until early adulthood at which time the force stays relatively level.[9-13] Males tend to have higher maximum bite force when compared to females at most ages.[9, 10, 12-14] Some evidence suggests that at certain ages females may have higher bite force, but this phenomenon may be related to gender difference in the onset of puberty and the associated muscle development during that period.

The studies also report that posterior bite force is highest and decreases as you move towards the incisor region.[11] The shift in maximum bite pressure from posterior to anterior may be explained by other factors. The mandible in relation to the rest of the skull acts much like a lever arm with the point of rotation at the temporomandibular joint and the main muscles of mastication located on the posterior portion of the mandible. As the point of contact moves away from the fulcrum, less force is generated. This explains why there is a decrease in bite force as you transition from molars to premolars to incisors. There is also a proprioceptive aspect to the periodontal ligament in that it contains specialized mechanoreceptors that are highly sensitive to stretch. Individual teeth have different amounts of periodontal ligament which results in different amounts of these mechanoreceptors. These mechanoreceptors may modify maximum bite force by initiating a biofeedback response in response to potential traumatic injury. The direction of force in respect to the long axis of a tooth may also influence the maximum bite force. Forces that are directed along or parallel to the long axis of the tooth are better able to distribute the force in a normal manner, as opposed to forces that are delivered to a tipped tooth. Tipped teeth may result in areas of excessive force which may initiate these biofeedback responses earlier than would be expected if forces were more evenly distributed.

Usui *et al*[13] reported that the facial skeletal growth pattern may alter the bite force. His group suggests that people with vertical growth or clockwise growth patterns have lower bite forces than those with a more normal relationship. This result can be explained by the anatomical orientation of the major muscles of mastication. People with more normal or counter clockwise pattern of growth will have muscle attachments at almost right angles to the occlusal plane which should provide some mechanical advantage. Conversely, people with a more clockwise direction or vertical direction of growth will have muscles that are orientated in a more oblique angle to the occlusal plane thus biting is not as efficient at the same level of force. Higher forces should be generated if the muscles are orientated perpendicular to the occlusal plane as no loss in force is generated in the horizontal plane.

The articles by Kamegai *et al* and Usui *et al* used Japanese subjects and there may be racial and environmental differences with North America. Japan tends to have a more homogeneous population compared to the heterogeneity of North America. The prevalence of certain types of malocclusions may also be considered as another potential source of debate. Another factor in these studies that has to be considered is the effect of diet on the masticatory system. Although diets in some parts of Asia are trending towards that of their western counterparts, it may be an important factor in developing differences in strength of masticatory muscles which would directly influence bite strength.

Although the pattern of relationship between age, gender and tooth position tend to be similar among investigators, the actual quantified values for maximum bite force showed some variation in the selected studies. Proffit *et al*[7] reported values of 320 +/- 184N for adult males whereas Kiliaridis *et al*[11] found values substantially higher at 807 +/- 140N. Even with the wide range of results, there is trend among the articles included in this review to have an average maximum bite force value of 500-600N for males and 400-500N for females with normal occlusion at the molar region (Table 3). All the studies reported large standard deviation which may statistically be an argument that there is in fact no clinically relevant difference in maximum bite force between males and females as concluded in certain articles.

Although the results of the studies in this systematic review tend to support one another, the difference in methodology make it difficult to directly compare the results. Many of the different researchers used different equipment to measure bite force. The device used to measure bite force was used by some groups only on one side where others used it on both. Other possible explanation of some of the variability may be due to the method and location of testing. Different groups used slightly different locations in the posterior even though they were considered in the molar region. All of these factors as well as variations in number of trials, duration of the test, and rest periods may have an effect on the large standard deviations seen between the studies.

The two articles that were included in the systematic review by Proffit were cited 133 times (adult article) and 59 times (children article). The reported maximum bite force of 320+/-184N for the normal adult group must be considered cautiously. These studies did not separate genders and pooled the data. As discussed earlier, men tend to have higher bite values compared to females and in this study there were twenty-five females and only fifteen males which would tend to lower what you may expect to be the blended average. The other criticism of these articles may be the small sample size used as compared to the significantly larger sample sizes used by other researchers. There was no reported statistical significance calculations or power calculations to establish that a sample size of 30 or 40 was adequate.[6, 7]

Braun *et al* in 1995 was the only group that did a reliability study to ensure that values were consistent within each participant. 25 randomly selected individuals were taken from the initial test group and retested 24 hours later. This group compared these results with the initial results to generate a correlation coefficient. They found a correlation coefficient of 0.89, which they reported as representing 79% of the variability that can be explained from the measured variables.[8] The remaining variability in the measurements may be explained by confounding factors. Some of these may include muscle fatigue, pain associated with biting the measurement instrument, and rest intervals.

Variation in muscle size has been suggested as being an important factor in maximum bite force.[18] The research tends to indicate that muscle growth increases with age until the late teens early twenties at which point there is a plateau. It may be difficult to factor muscle development into a study as each individual grows at their own pace which may not necessarily follow chronological age.

This is especially significant during the pubertal age range where maximal velocity of growth and development occur[17] It is important also to realize that there is not a direct relationship between muscle size and maximum bite force. Other factors such as sarcomere length, fiber type, and recruitment patterns may influence muscle activity.[14]

In summary, several groups have investigated bite force with different methodologies which produced a wide range of results. There are many factors that affect the maximum biting force in humans which may not be controllable. Even with these factors clouding the data, there were identified trends that are common in the articles selected for this review. Best efforts have been done to obtain all relevant articles; however even if additional studies were missed it is unlikely that they would significantly alter the identified trends.

2.5 Conclusions

- There is a lot of variability in the reported maximum bite force values resulting in a large standard deviation in the reported values
- A trend may be evident in the data suggesting a mean value (at the first molar) between 500-600N in males and 400-500N in females
- Males tend to have higher maximum bite force values when compared to females of the same age

- Bite force tends to increase with age until late teens early twenties where it tends to plateau
- Maximum bite force is highest in the posterior of the mouth and decreases as you move towards the anterior

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Chapter 3 – The Effect of Perturbations on Resistance to Sliding when using Conventional and Passive Ligated Brackets

3.1 Introduction

Resistance to Sliding is a term used to describe the combination of factors that resist the sliding movement at the bracket-wire interface. For moving objects, the resistance to sliding is characterised by the co-efficient of friction multiplied by the normal force applied perpendicular to the direction of movement or the force that pushes the objects together. When clearance exists between the wire and the sides of the slots, the normal force of friction is generated by the force of ligation. Ligation force presses the archwire against the base of the bracket slot creating two interfaces. That is the interface between the wire and the base of the slot, and the wire and the ligation method. The coefficient of friction is a constant variable that is unique to the materials that are interacting or pressing together. Factors which influence the coefficient of friction are surface roughness and hardness of the material. Orthodontic literature has been able to quantify this coefficient of friction between different bracket and archwire combinations.[1] It is generally agreed amongst the orthodontic community that stainless steel has the lowest coefficient of friction among archwire materials and beta titanium having the highest. Nickel titanium wires would fall in between steel and beta titanium in terms of coefficient of friction. For bracket materials, steel brackets have a lower coefficient of friction when compared to the ceramic/polymer type.

When second order angulations are introduced in the orthodontic system a unique situation is created when the arch wire contacts the opposite corners of the bracket wall. The angle that is created between the archwire and the bracket slot when this situation occurs is termed the critical contact angle (Θ_c). When $\Theta \geq \Theta_c$, the resistance to sliding is dominated by what Kusy terms as "binding."[2] As the angle between the archwire and bracket slot meet and exceed the critical contact angle, the friction that is created at this interface far exceeds that of the friction due to ligation. For this reason, at angles below Θ_c friction due to ligation is the major influence in resistance to sliding. This configuration can be referred to as the passive configuration. At angles that meet or exceed Θ_c, the friction between the archwire and the opposite corners of the bracket slots represent the dominant factor in resistance to sliding. Θ_c is influenced by the engagement index and the bracket index. The engagement index is represented as the ratio of the archwire size in the vertical dimension to the slot size also in the vertical dimension. The engagement index represents how much the wire fills the bracket slot. The bracket index is the ratio of the width of the bracket slot to the height of the bracket slot Fig 3-1. The critical contact angle can be calculated using values from the engagement index and the bracket index as referenced in Appendix C.[2]

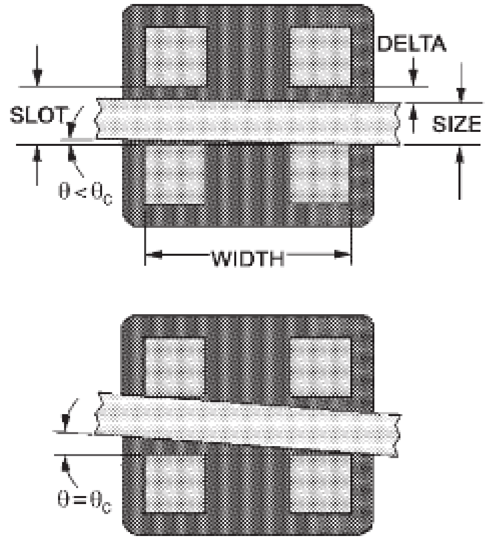

Fig 3-1. Schematic illustrations of an archwire-bracket couple: in the passive configuration, when $\Theta < \Theta_c$ (top) and in the active configuration (bottom), when $\Theta \geq \Theta_c$.[3] Copied from Kusy et al.

The friction due to the interaction between the archwire and the corner of the bracket wall continues to rise as the tip angle increases due to resistance to bending of the archwire. There comes a point where the angle becomes so great that deformation occurs in the wire or the bracket. It is at this point that there is a significant increase in friction associated with this deformation between the archwire and bracket which becomes the predominant factor in resistance to sliding. This deformation in materials causing the marked increase in friction is referred to as "notching" by Kusy.[2] This deformation is influenced by the composition of the contacting materials, which in the case of orthodontics are the bracket and the archwire.

There has been much debate among the orthodontic community in regards to advantages of passive ligated brackets compared to the conventional ligated brackets. Those on the side of passive ligation will argue that with less frictional influence, treatment efficiency improves.[4-6] Those on the side of conventional ligation will dispute these claims by suggesting that clinically there is no reported significant difference in treatment time between the two bracket types. One possible explanation as to the similar treatment times may be that although a passive system may be more efficient in the early stages of treatment (leveling and aligning) where lower friction may be desired, higher friction may be more desired in the final stages of treatment (finishing and detailing) which is the strength of the conventional system.[7] The only systematic review on this subject concludes that passive ligated brackets produce lower friction compared to conventional brackets only with small round wires, relatively well aligned arch, and absence of tip and torque issues. They go on to further conclude that in the presence of rectangular wire, tip and torque issues, or significant malocclusion there was insufficient evidence to make the claim that passive ligation was superior to conventional.[8] Many of the authors of frictional studies suggest that results may not be directly applied to the in vivo condition and that further research is needed to fully explore this complex environment.[9-11]

Another possible explanation as to why treatment times are similar between conventional and passive ligated brackets may be the influence of small displacements of the wire termed perturbations. As critical contact angle is exceeded, the predominant factors to resistance to sliding comes from binding and notching.[3] These perturbations temporarily unbind the wire from the bracket allowing sliding to occur. In vitro studies attempting to replicate perturbations have shown a decrease in resistance to sliding.[10, 12-14] Although the limited amount of scientific literature tends to support this concept, criticisms of experimental design and methodology force readers to accept conclusions with caution.

The aim of this study is to:

1. Investigate the effect of frequency of perturbations as it affects resistance to sliding when second order moments are introduced at the bracket wire interface at angulations above and below the critical contact angle.

2. Investigate the role of amplitude of perturbations on resistance to sliding when second order moments are created at the bracket wire interface at angulation below and above the critical contact angle

3. Compare the resistance to sliding between passive ligated brackets and conventional ligated brackets in the presence and absence of perturbations

3.2 Materials and Methods

To maintain consistency all experiments were conducted at room temperature by the single primary investigator (JW)

3.2.1 Testing Device

Resistance to sliding testing was conducted using a novel 3D frictional device designed by the Mechanical Engineering Department at the University of Alberta. This device is able to determine both force and moment at the bracket in all three dimensions accurately and repeatedly using a six-axis load cell. The x-axis is the direction that the wire is pulled through the bracket slot; it will run parallel to the slot. The z-axis will run perpendicular to the slot direction towards the investigator. The y-axis follows the direction of the long axis of the dowel and travels upwards. For the purposes of this experiment the directions of the 3 dimension planes as well as the angles created by rotation around these planes are represented in Fig 3-2.

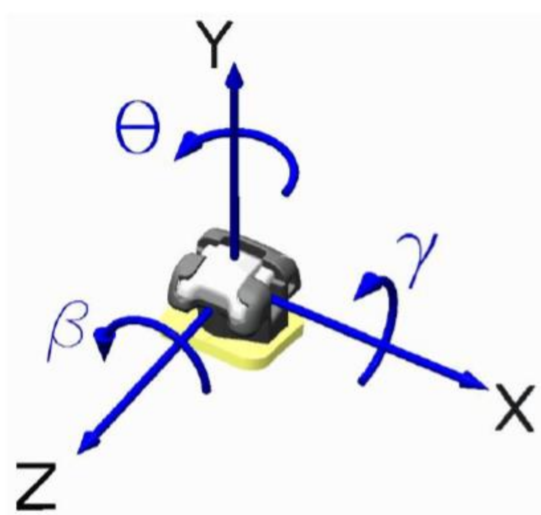

Fig 3-2. Diagramatic view of x, y, z axis orientated to bracket as well as angles Ө, γ, β.

The wire is attached to a micro-actuator which allows it to be pulled in the x-dimension at a predetermined consistent and constant speed. There are also 2 manual adjustments for the y and z dimensions to allow alignment of the wire to the bracket slot (Fig 3-3). The load cell which houses the test dowel is mounted on a micro adjusting rotating table (Fig 3-4). The micro-actuator and rotating turntable are operated by calibrated custom software designed by the Department of Mechanical Engineering at the University of Alberta. Parameters of the experiment such as speed of pull, rate of sampling, averaging of samples, and amount of rotation are predetermined by the investigator and inputted into the software using a configuration file. The configuration file is unique to each bracket and the information later stored and documented in the log file.

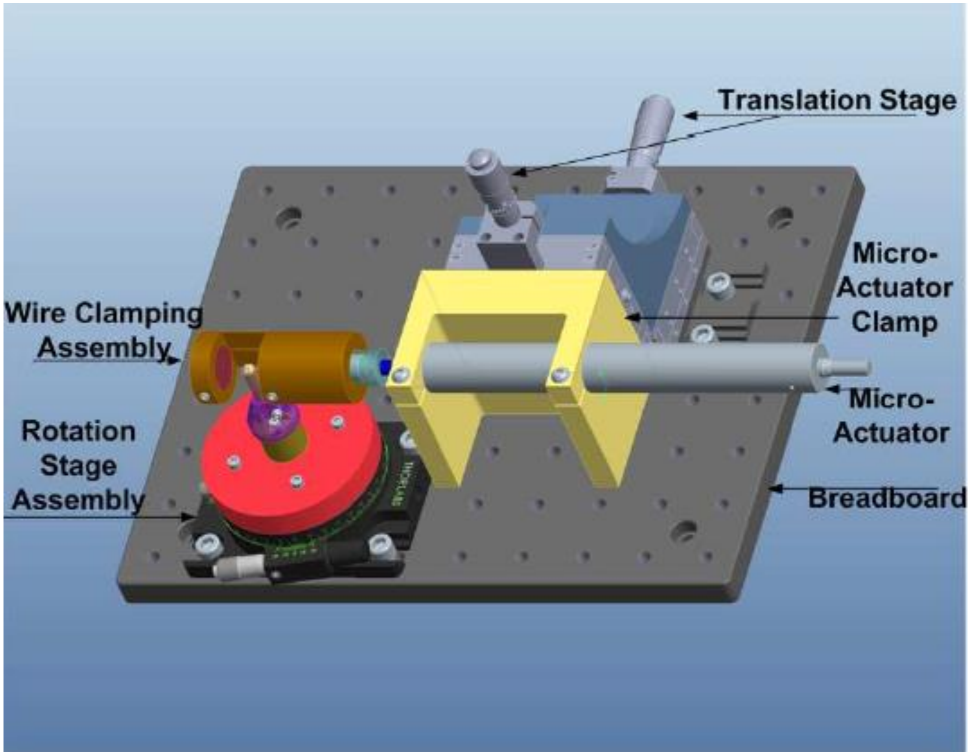

Fig 3-3. Diagram of custom 3D frictional device, University of Alberta.

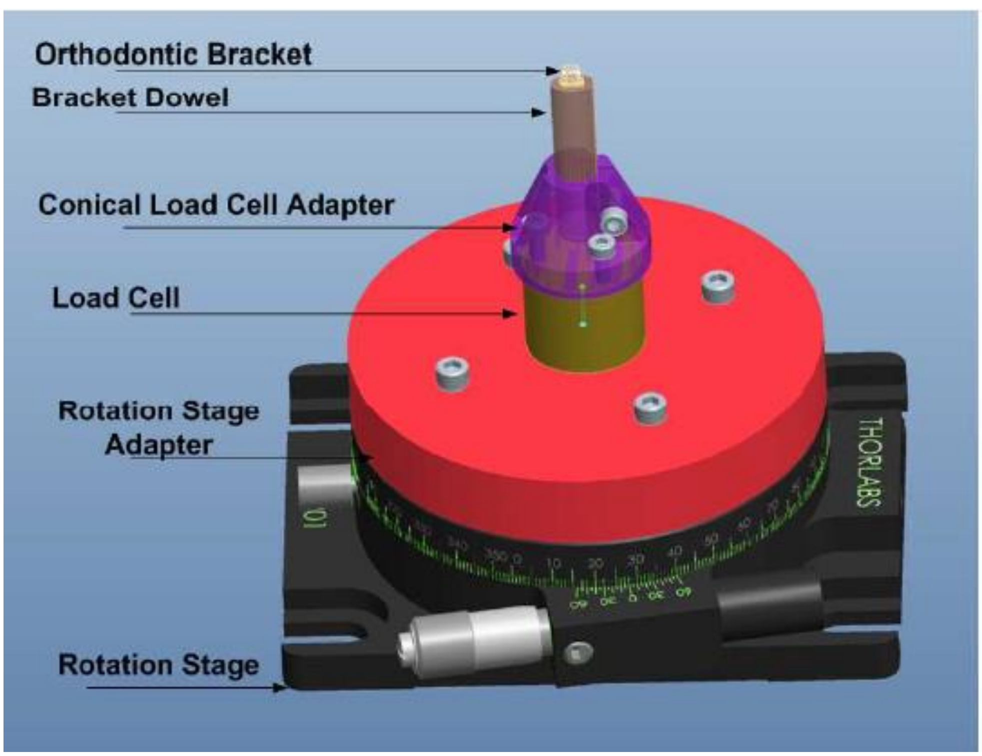

Fig 3-4. Diagram of the load cell, mounting apparatus, rotation stage, University of Alberta.

3.2.2 Perturbation Device

A custom perturbation device was designed by the Department of Mechanical Engineering at the University of Alberta (Fig 3-5). The device is composed of a rotating motor along with custom designed weighted discs. The weighted discs designed to fit on the head of the rotating motor have off center weights that creates imbalance and vibrations when spun. As the weight is moved farther away from the center of the disc, rotation causes greater perturbation amplitude. Additional weights were added to the perimeter of disc #6 to create additional amplitude in the perturbations. The rotating motor is run by a function generator (GW Instek GFG-8216A, New Taipei, Taiwan) connected to an oscilloscope (Tektronix TDS 2024B, Beaverton, OR). By adjusting the duty cycle on the generator and the amount of weight in the discs, the device can create distinct combinations of frequency and amplitude of perturbations. The device is mounted directly to the test dowel so that perturbations are delivered at the source which simulates force on a tooth. Perturbations generated by this device were felt at the level of the bracket along the x and z axis.

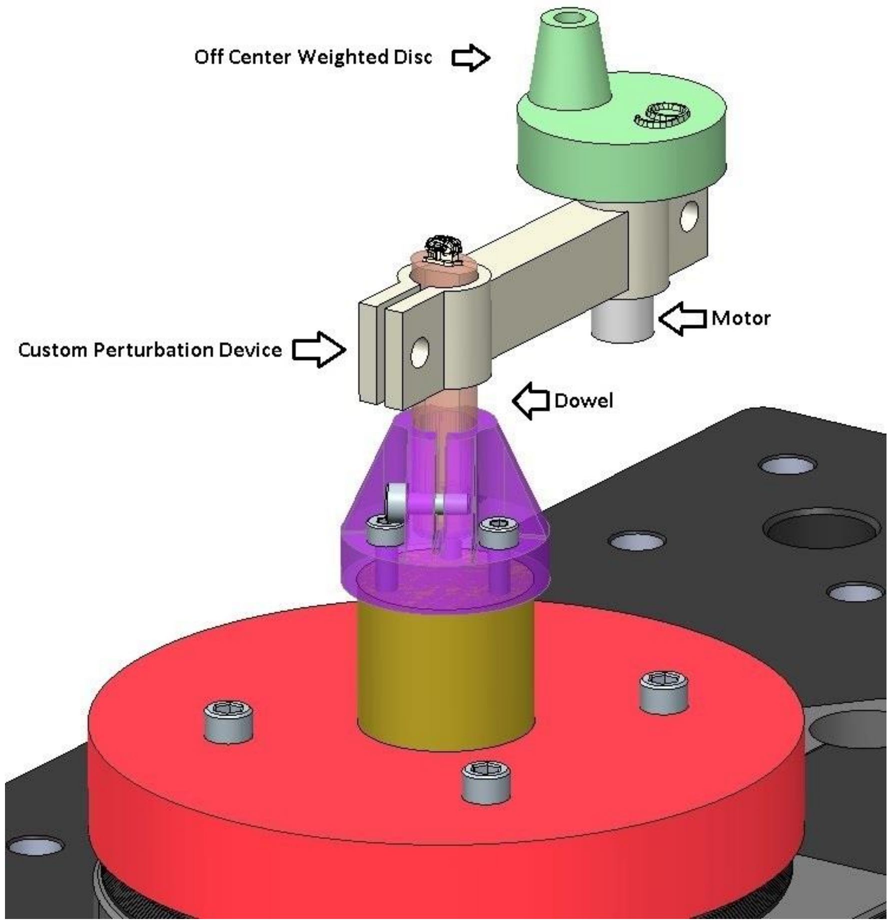

Fig 3-5. Schematic of custom perturbation device and off center weighted disk. University of Alberta.

3.2.3 Brackets and Dowels

For a medium effect size with a power =0.80 was selected, and n=30 per treatment group was determined to be an adequate sample size for this experiment (Appendix B). 150 maxillary left canine passive ligated brackets (Damon Q, Ormco, Orange, CA) with 0.022” slot size, +7^{o} torque, +5^{o} tip and 0^{o} rotation along with 150 maxillary left canine conventional ligated brackets (Unitek Victory Series Twin, 3M Unitek, Monrovia, CA) with 0.022” slot size, 0^o torque, 0^o tip, and 0^o rotation were used for this experiment. Stainless steel custom dowels (1/4” diameter, 1-1/4” length, McMaster-Carr, Elmhurst, IL) were cut by the Department of Mechanical Engineering laboratory. The mounting surface for the passive ligated brackets had a 7^o offset to compensate for the pre-existing torque prescription of the Damon Q brackets functionally converting it 0^o. Mounting surface for the conventional ligated brackets were flat as no compensations were needed for the existing prescription. Orientation of the bracket was possible as one surface extending the entire length of the dowel was flat. This flat surface allowed the dowel to be more accurately aligned when placed into the conical load cell adaptor which also had a corresponding flat surface. Prior to attaching the brackets to the dowels, all dowels were cleaned using a 98% ethanol solution to maximize bonding. Brackets were secured to the dowels using 5 minute epoxy (Steel Epoxy, LePage) cement. With the aid of magnification (3.5X surgical loupes), the center of the bracket was placed as close as possible to the center of the head of the dowel, and the line of the bracket slot was perpendicular to the line created by the flat surface that runs the length of the dowel. Each bracket-dowel combination was individually numbered to allow for randomization and blinding during data analysis.

3.2.4 Force/Moment Transformation

Because the load cell which records the data is at some distance away from the test bracket, transformation of the data must be done to determine the force/moment experienced at the level of the bracket. The force/moment data must be transformed along the z-axis from the load cell coordinate system to the level of the bracket. In addition, because the bracket is not mounted in the same plane as the load cell a 90 degree counter-clockwise rotation around the x-axis of the load cell is necessary to properly transform the data. As such the coordinate system at the level of the bracket is not the same as at the level of the load cell Fig 3-6.

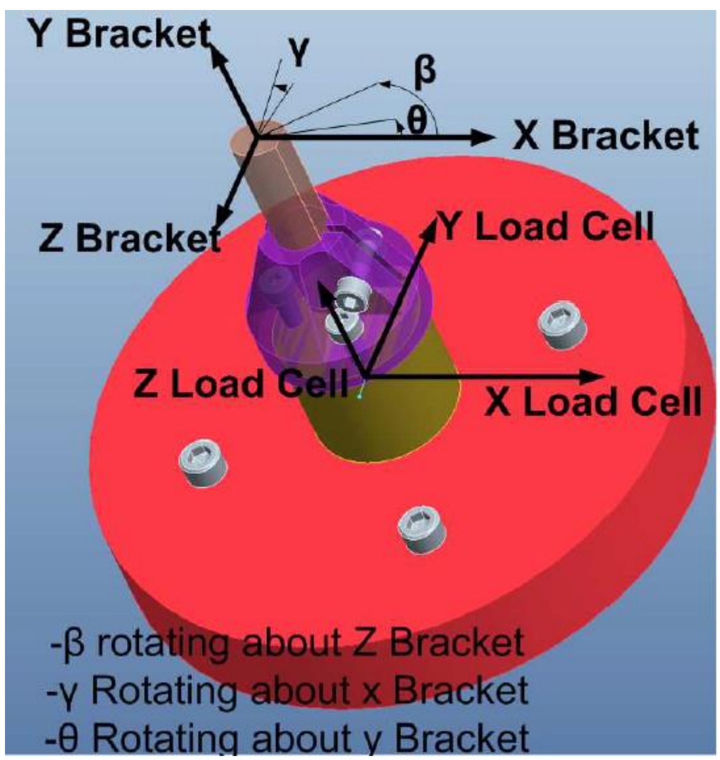

Fig 3-6. Coordinate systems at the load cell versus coordinate system at the level of the bracket.

The actual transformation involves complex mathematics that was developed by the Department of Mechanical Engineering at the University of Alberta for their torquing device and then modified for the frictional device.[15]

3.2.5 Imaging of Brackets

Because the bracket is at some distance from the load cell and the bracket may not be on the true center, it is necessary to know the precise position and orientation so that compensations can be made in the programming. Dowel lengths and diameters were measured using a micrometer 3 separate times and the values averaged to minimize measuring error. Each individual bracket-dowel combination was imaged in 3 planes using a CCD camera (Bausch&Lomb, Rochester, NY) under magnification (Fig 3-7). These images were then imported into a custom image measuring program written in MatLab designed by the mechanical engineering department at the University of Alberta. This program allowed the investigator to identify the offsets of the bracket in the x, y, and z axis (dx, dy, and dz) as well as the Θ, β, and γ. These values were stored in the configuration file unique to each bracket-dowel combination as an offset to standardize each sample.

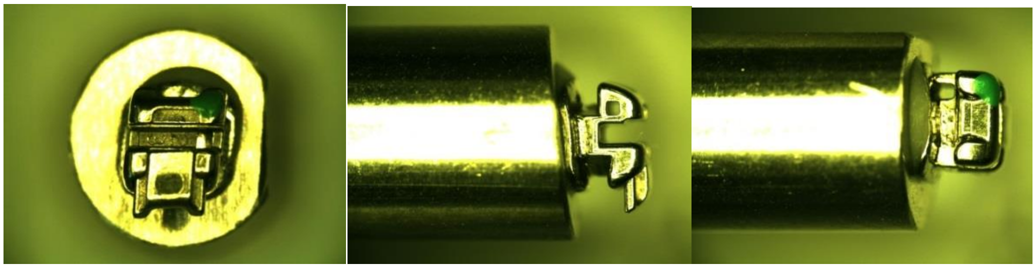

Fig 3-7. Example of 3 views of bracket-dowel taken by CCD camera. Notice in this example the passive ligated bracket is offset off the base, and that flat edge on top view allows for orientation of the bracket. University of Alberta.

3.2.6 Testing Procedure

150 Conventional ligated brackets were randomly assigned into each of the 5 test groups (n=30 per group) by a third party. This process was repeated for the 150 passive ligated brackets resulting in a total of 10 equal sized test groups (Table 3-1).

Test Condition	Frequency/Amplitude of Perturbations	Sample size (total 300)
LF/LP Conventional	Frequency = 7.3Hz Force-RMS = 0.102N	30
LF/LP Passive	Frequency = 7.3Hz Force-RMS = 0.102N	30
HF/LP Conventional	Frequency = 14.2Hz Force-RMS = 0.100N	30
HF/LP Passive	Frequency = 14.2Hz Force-RMS = 0.100N	30
LF/HP Conventional	Frequency = 21.2Hz Force-RMS = 0.860N	30
LF/HP Passive	Frequency = 21.2Hz Force-RMS = 0.860N	30
HF/HP Conventional	Frequency = 47.0Hz Force-RMS = 0.882N	30
HF/HP Passive	Frequency = 47.0Hz Force-RMS = 0.882N	30
Control Conventional	Frequency = 0Hz Force-RMS = 0N	30
Control Passive	Frequency = 0Hz Force-RMS = 0N	30

Table 3-1. Table of test conditions and description of frequency and amplitude of perturbations for each test condition as well as sample size per group.

Amplitude chosen for both low and high perturbation group consisted of levels which clinically are able to initiate tooth movement without excessive trauma. Initial testing was done to determine the amount of force that the perturbations would deliver by measuring the forces and moments at the level of the bracket without a wire. Because the perturbations were generated by a rotating disc, the force pattern was cyclical. Averaging these values would result in a net effective force of 0. Instead, the root mean squared (RMS) value was used to establish the force value of the perturbations. Several combinations of rotating wheels and frequencies were tested and final test conditions were chosen based on similar force-RMS values with different frequencies. Because of the cyclical nature of the perturbation, the rate of sampling allows enough time that the force associated with the perturbations averages out to 0 leaving only the force associated with resistance to sliding.

Each bracket was randomly assigned into one of the test conditions. Once the bracket-dowel complex was mounted to the load cell, the custom perturbation device was secured so that it was flush to the dowel surface and perpendicular to the bracket slot. The appropriate sized perturbation disc was selected and secured to the rotating motor head. The 18x25 stainless steel wire (Ormco, Orange, CA) was secured to the micrometer and using the translation adjustments the wire was positioned over the bracket slot. Stainless steel wire was selected for this experiment as this is the material that is typically used for sliding mechanics due to the fact that it has the lowest coefficient of friction among the materials used in orthodontic wires.[16] Wire dimension was selected as per previous published work and protocol by Fathimani.[17] With the aid of a Bausch & lomb microscope (Bausch & Lomb, Rochester, NY) and the micro-adjustments on the rotating table, the bracket slot was also lined up parallel to the wire so that equal space existed above and below the wire. The wire was also set so that it was not contacting the bracket base prior to closing the gate on the passive system or applying the elastomeric ligation in the conventional system. In the passive ligated system, a gate design was closed to secure the wire to the bracket. In the conventional ligated bracket a standard elastomeric ligatures (silver color power O modules, size 0.120, Ormco, Orange, CA) was used to secure the wire to the bracket. To ensure that elastomeric ligatures were stretched the same amount and that no distortions or twisting occurred when securing the bracket wings a straight shooter ligature gun (TP Orthodontics, La Porte, IN) was used. Θ was tested between 0^{o} and 6^{o} in 1^{o} increments at a sampling rate of 4000Hz at 500 samples per channel. Data collection for each sample occurred over a total distance of 0.2mm at each angle increment with the wire speed set at 0.05mm/sec.

3.2.7 Data Collection

The frictional device is able to acquire both force and moments that occur in all 3 planes of space. That is forces in x,y and z axis (Fx, Fy, Fz) as well as the associated moments (Mx, My, and Mz). Example of the raw output can be seen in Appendix F. As previously stated measurements are taken at the level of the load cell and transformed to the level of the bracket. As the bracket begins to tip and second order moments are produced, forces in the x and z axis are created with minimal influence from forces in the y-axis. Because forces were generated in only the x and z axis, we determined that the resistance to sliding in this scenario to be the resultant force vector created by Fx and Fz. This was mathematically determined using the equation:

$$\text{Resistance to Slide (RS)} = \sqrt{(Fx)^2 + (Fz)^2}$$

The data created by this experiment was subject to averaging at 2 stages of collection. The first occurs when the data acquisition collected the data and averaged every 500 samples to produce a single value. Sampling at a high rate and averaging several of the samples allows us to reduce some of the variability caused by the perturbations. All values with the same degree of Θ were averaged in a spreadsheet to produce a single mean value for each angle tested. The raw data was recorded in a log file created by the frictional device software and later interpreted using spreadsheets, and IBM SPSS.

3.2.8 Statistical Analysis

The statistical product and service solution program (SPSS, IBM, Armonk, NY) by IBM was used to analyse the data gathered in this experiment. Data was initially statistically evaluated for normality and homogeneity and to determine if model assumptions have been satisfied. Equal covariance-variance assumptions were not met as evidence by box plots (Appendix E), levene's test, and boxes M test. Although not all model assumptions were met, the large sample size, the equal number in each group, and the robustness of the test itself justify using repeated measures analysis of variance (ANOVA) to determine both main effects as well as interaction effects. Because equal variance was not satisfied, the Tamhane post hoc test was chosen to analyse the planned comparisons. To properly answer the research question, angulations were fixed and bracket and condition were evaluated using separate two-way ANOVA. The level of significance when comparing bracket types was set to $\alpha = 0.05$. When comparing test conditions, the main research question consisted of a planned pairwise comparison between test conditions and control. As such we have four planned comparisons and to prevent the inflation of Type I error rate we set the significance level to $\alpha = 0.05/4 = 0.0125$ when investigating test conditions.

3.3 Results

Data collected consisted of repeated measures of resistance to sliding at 7 different angulations starting at 0 degrees and increasing by 1 degree for a range of 0 to 6 degrees. An equation for critical contact angle was used to determine the Θ_c for both the conventional and passive ligated bracket (Appendix C).[3] Θ_c was determined to be 2.08 degrees for the passive ligated bracket (Damon Q, Ormco, Orange, CA), and 1.81 degrees for the conventional ligated bracket (Victory Series Twin, 3M, Monrovia, CA). To investigate the role of perturbations on resistance to sliding, the research group chose 2 angulations to investigate. One angulation was below the Θ_c (0 degrees) and the other above the Θ_c (6 degrees).

Results from repeated measures ANOVA suggest that there is strong evidence to support that there is a difference between conventional ligated and passive ligated brackets when testing for resistance to sliding ($p < 0.001$). There is also strong evidence to suggest that there is a difference between test conditions when testing for resistance to sliding ($p < 0.001$). The repeated measures ANOVA also showed that there is moderate evidence to suggest that there is interaction between bracket type and test conditions as it relates to resistance to sliding ($p = 0.028$). A Profile plot was generated to further investigate the possible source of this interaction term (Fig 3-8).

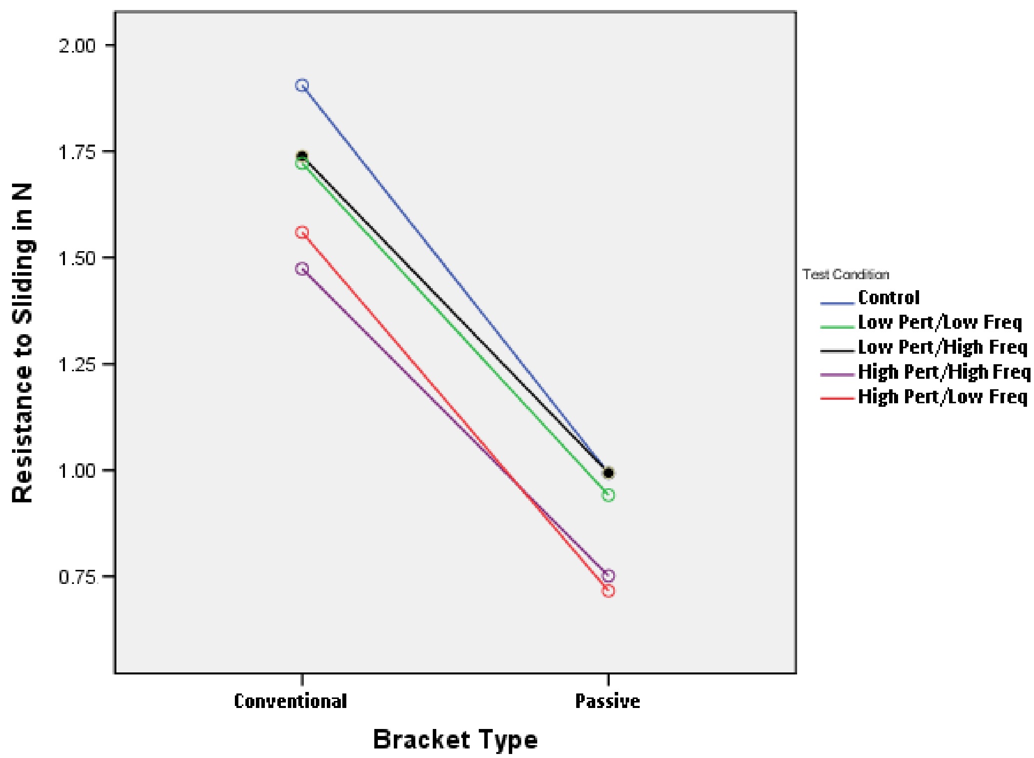

Fig 3-8. Box Plot of Bracket Type and Test Condition

Evaluation of the box plot reveals that resistance to sliding is higher for conventional brackets when compared to passive brackets under all test conditions as well as controls. The plot also shows that the high perturbation/high frequency and the high perturbation/low frequency test conditions have the greatest ability to reduce resistance to sliding for both conventional and passive brackets when compared to both control and low perturbation groups. Interactions between test conditions and bracket types are illustrated by the lack of parallel lines between the test conditions.

Two way ANOVA was performed to evaluate the relationship between brackets and conditions with a fixed angulation of 0 degrees. Further evaluation included pairwise comparisons of the test groups based on the post hoc test results. Results show that for conventional brackets there was a statistical difference between all treatment conditions compared to control $p<0.001$ (Table 3-2). Control test group showed the highest resistance to sliding when compared to any of the test groups when using conventional brackets. The largest reduction in resistance to sliding was seen in test groups that utilized high amplitude perturbations. Although the slope of the line of the test conditions follows that of the control, the presence of perturbations shifts the lines to the right when compared to control for all test conditions (Fig 3-9).

Table 3-2. Table of mean resistance to sliding (RS) for test groups, mean difference in RS for test groups compared to controls for conventional ligated brackets at 0 degrees, p-values, and 95% confidence intervals.

Test Condition	**Mean RS in N Standard Deviation (SD)**	**Mean difference RS (Control* – Test) in N**	**P-value**	**95% Confidence Interval in N**
Low Perturbation / Low Frequency	0.551 (0.110)	0.077	<0.001	0.044 to 0.109
Low Perturbation / High Frequency	0.510 (0.063)	0.118	<0.001	0.085 to 0.150
High Perturbation / High Frequency	0.261 (0.064)	0.367	<0.001	0.335 to 0.400
High Perturbation / Low Frequency	0.317 (0.092)	0.311	<0.001	0.278 to 0.343

Level of Significance set at α=0.0125, * = 0.628N (0.091)

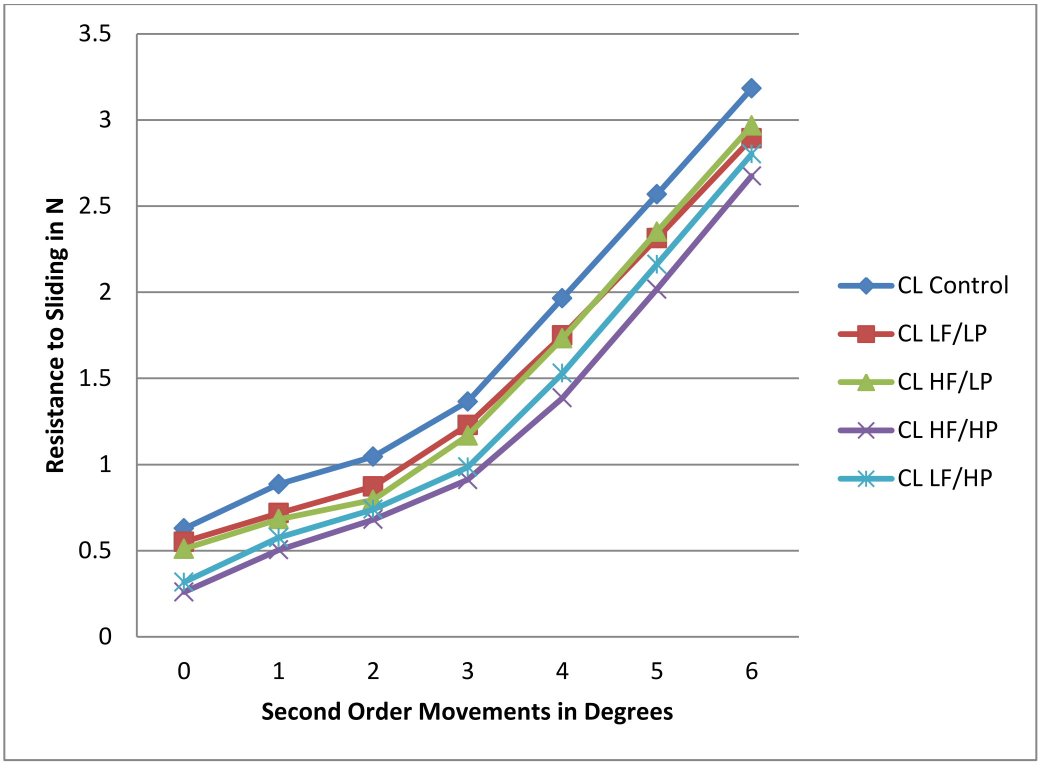

Fig 3-9. Graph of second order movement versus resistance to sliding for conventional ligated brackets (CL). LF = Low frequency, HF = High frequency, LP = Low perturbations, HP = High perturbation.

For passive ligated brackets there was no statistical difference between treatment groups and control at 0 degrees at α = 0.0125 for all test conditions with the exception of the high perturbation / high frequency group. It should be noted that the significance of this result (p=0.010) was extremely close to the set level of alpha (0.0125). This was an expected result as resistance to slide in a passive ligated system should be nominal at this angulation (Table 3-3). Resistance to sliding between all test conditions were relatively similar until critical contact angle was achieved. When $\Theta > \Theta_c$ test conditions which contained high amplitude perturbations showed a reduction in resistance to sliding which was not observed in test conditions which contained low amplitude perturbations (Fig 3-10).

Table 3-3. Table of mean resistance to sliding (RS) for test groups, mean difference in RS for test groups compared to controls for passive ligated brackets at 0 degrees, p-values, and 95% confidence intervals.

Test Condition	**Mean RS in N Std Dev (SD)**	**Mean difference RS (Control* – Test) in N**	**P-value**	**95% Confidence Interval in N**
Low Perturbation / Low Frequency	0.020 (0.007)	-0.004	0.792	-0.037 to 0.028
Low Perturbation / High Frequency	0.008 (0.008)	0.008	0.648	-0.025 to 0.040
High Perturbation / High Frequency	0.058 (0.050)	-0.043	0.010	-0.075 to -0.010
High Perturbation / Low Frequency	0.031 (0.016)	-0.015	0.361	-0.048 to 0.017

Level of Significance set at α=0.0125, * = 0.015N (0.038)

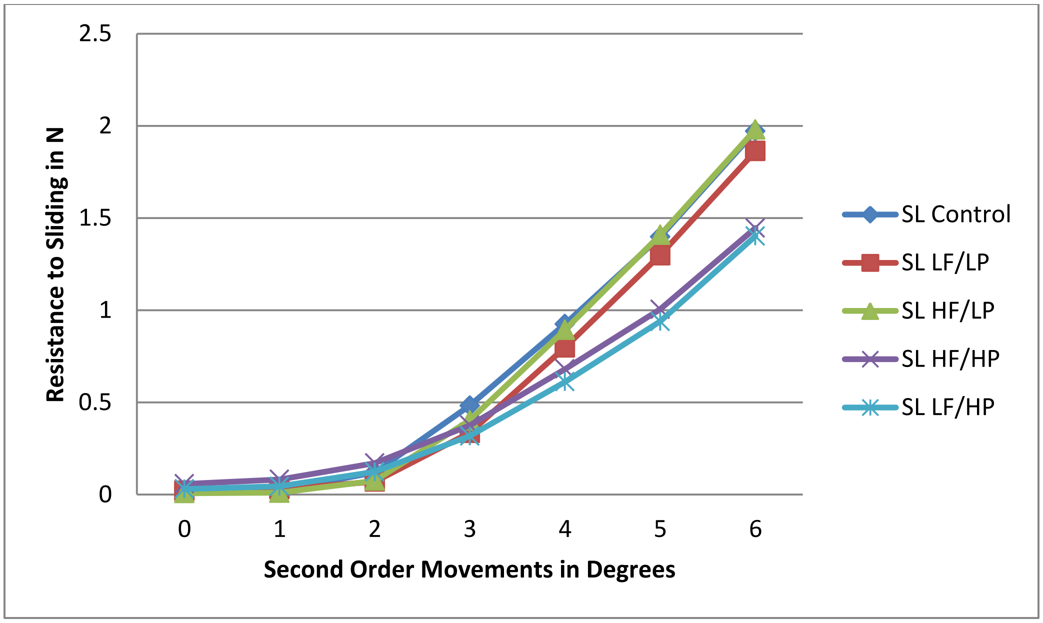

Fig 3-10. Graph of second order movement versus resistance to sliding for passive or self ligated brackets (SL). LF = Low frequency, HF = High frequency, LP = Low perturbations, HP = High perturbation.

Evaluation of the relationship between brackets and conditions with a fixed angulation of 6 degrees was also evaluated with a two-way ANOVA followed by pairwise comparison post hoc test. For conventional brackets, all treatment groups were statistically significant with the exception of the low perturbation/low frequency condition (p=0.017). We note that for the low perturbation/low frequency group the evidence is weak as the p-value (0.017) is extremely close to the set alpha (0.0125) for this experiment. There was no statistical difference between the groups with low levels of perturbations p=0.407 (Appendix D). Largest differences in reduction in mean resistance to sliding occurred in both high perturbation groups. The High perturbation/high frequency was the largest reduction at 0.495N with a 95% CI (0.672, 0.319) followed by the high perturbation/low frequency group at a reduction of 0.381 N with a 95% CI (0.557, 0.204) (Table 3-4). There was no statistically significant difference when comparing both high perturbation groups p=0.201 (Appendix D).

Table 3-4. Table of mean resistance to sliding (RS) for test groups, mean difference in RS for test groups compared to controls for conventional ligated brackets at 6 degrees, p-values, and 95% confidence intervals (CI).

Test Condition	**Mean Test RS in N Std Dev (SD)**	**Mean difference RS (Control* – Test) in N**	**P-value**	**95% Confidence interval in N**
Low Perturbation / Low Frequency	2.892 (0.413)	0.290	0.001	0.113 to 0.466
Low Perturbation / High Frequency	2.967 (0.365)	0.215	0.017	0.039 to 0.392
High Perturbation / High Frequency	2.687 (0.411)	0.495	<0.001	0.319 to 0.672
High Perturbation / Low Frequency	2.801 (0.422)	0.381	<0.001	0.204 to 0.557

Level of Significance set at α=0.0125, * = 3.18N (0.351)

For passive ligated brackets at 6 degrees, low perturbation/low frequency and low perturbation/high frequency groups did not show statistical difference when compared to control p=0.229 and p=0.924 respectively (Table 3-5). There was also no statistical difference between both groups that had low perturbation levels p=0.194 (Appendix D). There was however statistically significant difference between both high perturbation groups when compared to controls both with p<0.001. There was no statistical difference when comparing the groups which contained high perturbations p = 0.631(Appendix D).

Table 3-5. Table of mean resistance to sliding (RS) for test groups, mean difference in RS for test groups compared to controls for passive ligated brackets at 6 degrees, p-values, and 95% confidence intervals (CI).

Test Condition	**Mean Test RS in N, Std Dev (SD)**	**Mean difference RS (Control* – Test) in N**	**P-value**	**95% Confidence Interval in N**
Low Perturbation / Low Frequency	1.863 (0.179)	0.108	0.229	-0.068 to 0.284
Low Perturbation / High Frequency	1.980 (0.246)	-0.009	0.924	-0.185 to 0.168
High Perturbation / High Frequency	1.44 (0.427)	0.526	<0.001	0.350 to 0.702
High Perturbation / Low Frequency	1.40 (0.265)	0.569	<0.001	0.393 to 0.745

Level of Significance set at α=0.0125, * = 1.971N (0.290)

When comparing conventional ligated brackets to passive ligated brackets with respect to resistance to slide, there was a statistically significant difference between bracket types in all test conditions at both 0 degrees and 6 degrees. Conventional ligated brackets displayed a statistically higher level of resistance to slide under all test conditions and angulations compared to passive ligated brackets. The difference in resistance to sliding between conventional and passive ligated brackets is the smallest under the high perturbation test group independent of frequency. The largest difference between bracket types occurred with the control group, with the low perturbation groups inbetween. This difference between high perturbation and low perturbation is not seen at 6 degrees (Table 3-6, 3-7).

Table 3-6. Table of mean resistance to sliding (RS) for conventional brackets, mean RS for passive brackets, mean difference in RS at 0 degrees for conventional brackets compared to passive ligated brackets, p-values, and 95% confidence intervals (CI).

Test condition	**Mean RS in N conventional Std Dev (SD)**	**Mean RS in N Passive Std Dev (SD)**	**Mean difference RS (conventional – passive) in N**	**P-Value**	**95% CI in N**
Control	0.628 (0.091)	0.015 (0.038)	0.613	<0.001	0.580 to 0.645
Low Perturbation / Low Frequency	0.551 (0.110)	0.020 (0.007)	0.532	<0.001	0.499 to 0.564
Low Perturbation / High Frequency	0.510 (0.063)	0.008 (0.008)	0.503	<0.001	0.470 to 0.535
High Perturbation / High Frequency	0.261 (0.064)	0.058 (0.050)	0.203	<0.001	0.170 to 0.235
High Perturbation / Low Frequency	0.317 (0.092)	0.031 (0.016)	0.287	<0.001	0.254 to 0.319

Level of Significance set at $\alpha=0.05$

Table 3-7. Table of mean resistance to sliding (RS) for conventional brackets, mean RS for passive brackets, mean difference in RS at 6 degrees for conventional brackets compared to passive ligated brackets, p-values, and 95% confidence intervals (CI).

Test Condition	Mean RS conventional in N Std Dev (SD)	Mean RS in N passive Std Dev (SD)	Mean difference RS (conventional – passive) in N	P-value	95% CI in N
Control	3.182 (0.351)	1.971 (0.290)	1.211	<0.001	1.035 to 1.387
Low Perturbation / Low Frequency	2.892 (0.413)	1.863 (0.179)	1.029	<0.001	0.853 to 1.206
Low Perturbation / High Frequency	2.967 (0.365)	1.980 (0.246)	0.987	<0.001	0.811 to 1.163
High Perturbation / High Frequency	2.687 (0.411)	1.445 (0.427)	1.242	<0.001	1.065 to 1.418
High Perturbation / Low Frequency	2.801 (0.422)	1.402 (0.265)	1.399	<0.001	1.223 to 1.576

Level of Significance set at $\alpha=0.05$

Graphs of resistance to sliding and second order angulations for each test condition provide a visual representation of the statistical results. The lines for test conditions which contain low amplitude perturbations tends to follow that of their respective control at all angulations tested irrespective of frequency (Fig 3-11 and Fig 3-12). This suggests that low perturbation does not significantly affect resistance to sliding when compared to controls irrespective of frequency.

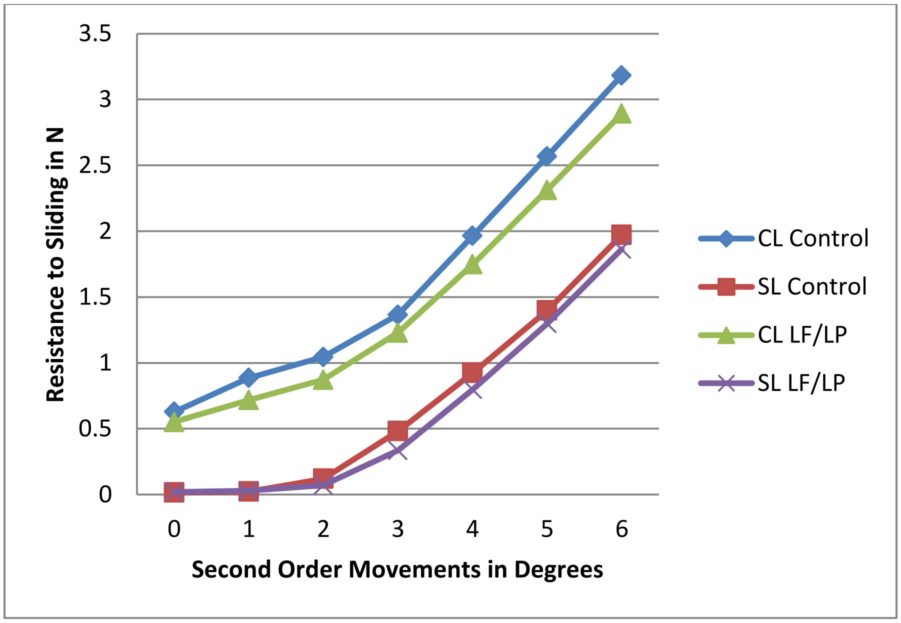

Fig 3-11. Graph of second order movements versus resistance to sliding comparing conventional ligated (CL) brackets to self-ligated or passive brackets (SL) under the Low frequency/Low perturbation (LF/LP) test condition.

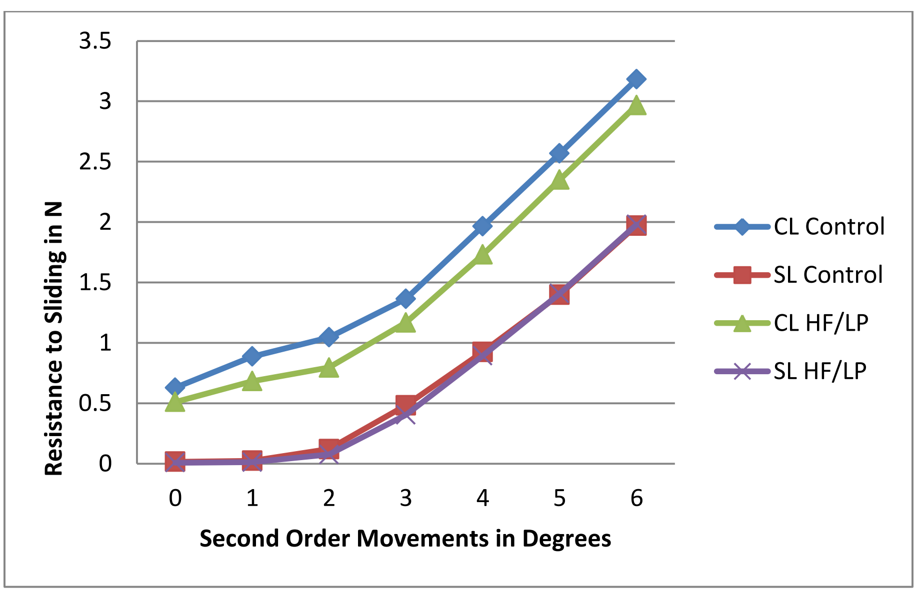

Fig 3-12. Graph of second order movements versus resistance to sliding comparing conventional ligated (CL) brackets to self-ligated or passive brackets (SL) under the High frequency/Low perturbation (HF/LP) test condition.

As amplitude of perturbation seems to have more effect on resistance to sliding than frequency when compared to controls, further details are presented for the high perturbation test groups. In the high perturbation/high frequency test condition, there was a 59% reduction in mean resistance to slide with a value of 0.261 +/- 0.063 N compared to 0.628 +/- 0.091 N for the conventional bracket group at 0 degrees. As suspected from the profile plots and further verified by post hoc pairwise comparison, resistance to sliding for passive ligated brackets did not show large variation between this test group and control at 0 degrees. There was a 16% reduction in mean resistance to slide with a value of 2.69 +/- 0.41 N compared with the control 3.18 +/- 0.35 N for conventional brackets at 6 degrees. Passive ligated brackets showed a mean reduction in resistance to slide of 27% with a value of 1.46 +/- 0.43 N compared to 1.97 +/- 0.29 N for the control at 6 degrees. There is a clear difference in the lines between test condition compared to controls as $\Theta > \Theta_c$ (Fig 3-13). As predicted, for passive ligated brackets the resistance to sliding was similar for test condition compared to control until Θ_c was achieved.

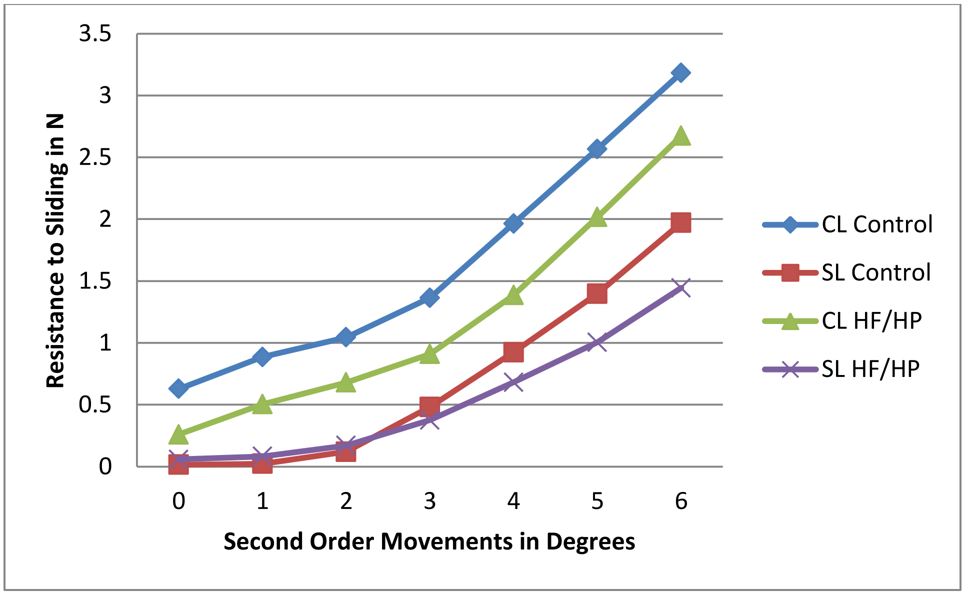

Fig 3-13. Graph of second order movements versus resistance to sliding comparing conventional ligated (CL) brackets to self-ligated or passive brackets (SL) under the High frequency/High perturbation (HF/HP) test condition.

In the high perturbation/low frequency test condition, there was a 50% reduction in mean resistance to slide with a value of 0.317 +/- 0.091 N compared to 0.628 +/- 0.091 N for conventional brackets at 0 degrees. There was no statistically significant difference in resistance to sliding for passive ligated brackets at 0 degrees compared to the control value of 0.015 +/- 0.038 N. For conventional brackets at 6 degrees, there was a 36% reduction of mean resistance to sliding of 2.80 +/- 0.422 N compared to control value of 3.18 +/- 0.35 N. Passive ligated brackets showed a mean reduction in resistance to sliding of 28% with a value of 1.40 +/- 0.26 N compared to 1.97 +/- 0.29 N for control. As with the other test group that contained high amplitude perturbations, as $\Theta > \Theta_c$, there was statistically significant decrease in resistance to sliding when compared to controls (Fig 3-14). For passive ligated brackets as predicted, resistance to sliding was similar between test condition and control until Θ_c was achieved.

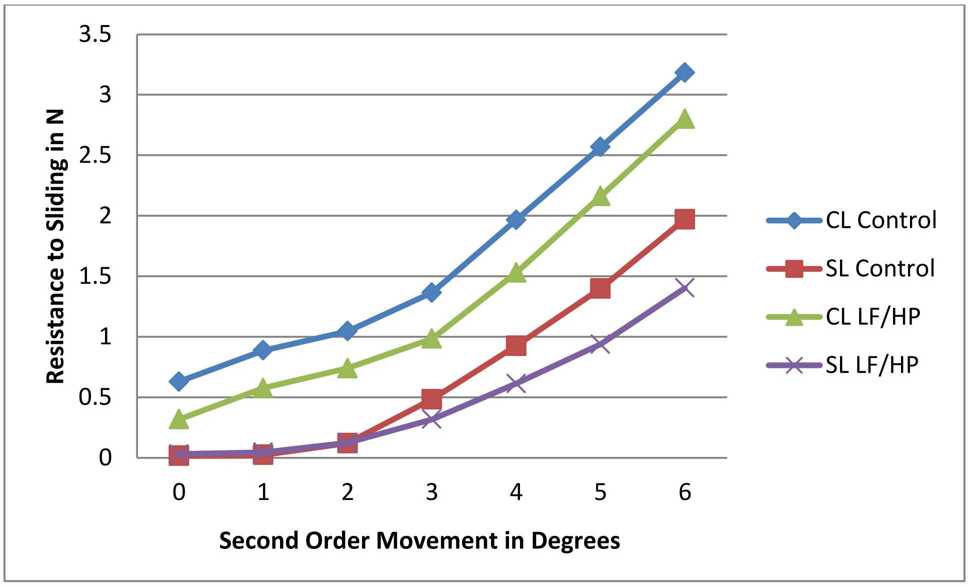

Fig 3-14. Graph of second order movements versus resistance to sliding comparing conventional ligated (CL) brackets to self-ligated or passive brackets (SL) under the Low frequency/High perturbation (LF/HP) test condition

3.4 Discussion

Previous experiments done by different investigators using different methodology all seem to come to the same conclusion; that perturbations reduce the resistance to sliding.[10, 12-14] The present study provides a reproducible and accurate quantification of the effect of perturbation. This experiment not only allows us to investigate the role of perturbations on resistance to sliding, but also allows us to observe possible difference between conventional and passive ligated brackets. The angulations of 0 and 6 degrees were chosen to represent angles above and below the critical contact angle.

It is clear that in our experiment, there is increased resistance to sliding using a conventional ligated bracket compared to a passive ligated bracket under any test condition or angulation. This is the result of the additional friction within the bracket wire interface caused by the force from the ligation (elastomeric in our example). As angulation increases and surpasses the critical contact angle, friction due to ligation plays a smaller role in resistance to sliding when compared to the friction associated with binding and notching (due to bracket and wire design).[2, 18] Perturbations of any amplitude or frequency reduce the resistance to sliding when using a conventional ligated system; however larger reductions were seen in test groups that utilized high amplitude perturbations. Because passive systems are designed to produce minimal to no resistance when $\Theta < \Theta_c$, we did not expect perturbations to have much effect at these angles. We did observe that for passive brackets when $\Theta > \Theta_c$, perturbations of high amplitude independent of frequency produced a reduction in resistance to sliding where low amplitude perturbations did not. Although high amplitude perturbations have the largest effect on resistance to sliding for both conventional and passive ligated brackets at both tested angulations, there was a larger net reduction in resistance to sliding in passive ligated brackets at 6 degrees. The data for this experiment suggests that amplitude of perturbations may have a more significant role in reducing resistance to sliding than frequency, and that higher perturbations are more effective than lower levels of perturbation.

The wire was pulled at a rate of 0.05mm/sec which is significantly faster that what is seen clinically (1mm/month). Therefore it is important to consider the time scale carefully when designing the experiment. Perturbations must be delivered at a higher frequency to compensate for the faster rate of wire pull in order to keep ratios of perturbations per mm movement consistent. Perhaps a more meaningful way of describing the rate of perturbations is to measure the number of perturbations per millimeter of wire movement, rather than the number of perturbations per second. By measuring the rate of perturbations in this manner, the speed at which the wire would no longer be a factor.

3.5 Clinical Implications

Friction resulting from ligation force has long been felt within the orthodontic community as a major contributor to resistance to sliding.[7] It is now better understood that this source of friction has a primary role only when $\Theta < \Theta_c$.[2] Brackets and wires within the biological system are rarely straight in the initial stages of treatment. This creates first and second order bends in the archwire and in most clinical situations friction (binding) associated with forces acting between the wire and bracket slot sides are important. There is much debate whether passive ligated brackets are more efficient when compared to conventional ligated brackets due to reduction in friction within the system.[8] We as clinicians must have a better working understanding of the role of various sources of friction that resist movement of the bracket (tooth) along the archwire, so as to maximize treatment efficiencies or decrease potential side effects. Perturbations occur intra-orally throughout the day as teeth contact during mastication, clenching and bruxism. Human bite force and frequency vary greatly between individuals, however bite force which translates into amplitude of the perturbation far exceed what the testing equipment can tolerate. From our systematic review, mean maximum bite force can range between 400-600N. It is noteworthy that even perturbations of 0.882N (our high amplitude perturbation group which is a fraction of the force that humans are capable of generating resulted in reduction of resistance to sliding. Since perturbation forces and associated displacement of the teeth (bracket) in mastication are significantly larger than what was used in this experiment it is quite plausible that forces due to masticatory perturbations may have a major effect in reducing resistance to sliding resulting in more efficient tooth movement. The results of this experiment have shown that high amplitude perturbations have the ability to reduce resistance to sliding suggesting that perhaps activities such as gum chewing may increase efficiency of treatment, further investigation would need to be done. Companies such as Acceledent® have already begun marketing devices that introduce vibrations (20 grams of force at 30 Hz) with the claim of accelerating tooth movements by up to 50%. 20 grams is equivalent to roughly 0.2N, and using a frequency of 30Hz would simulate most closely with our low perturbation/high frequency test condition. As we have concluded that frequency does not have as significant a role in reduction of resistance to sliding when compared to amplitude of perturbation this device may result in better clinical results if introduced vibrations had more force. Understanding the role of perturbations on resistance to sliding will also allow clinicians the ability to make more informed decisions on the type of brackets they choose to use in their offices.

3.6 Limitations of Study

Caution must always be exercised when conferring results from in vitro studies to an in vivo model. The oral environment is extremely complex and although our experiment is able to account and measure several factors previously not quantified it still represents a very simplistic model. Because of the variability of frequency and amplitude of bite force in individuals, a limitation of this study was the determination of the test groups for perturbations used in this study. This model measures the resistance to sliding only on a single bracket which is an obvious oversimplification of the oral situation. Results from this experiment may not be representative when multiple teeth are involved. The biology and physiology of teeth and bone are also factors which are difficult to control. Teeth and bone are not as rigid as metal dowels, and the effect of periodontal ligament space is difficult to reproduce accurately in the lab setting. 3M Victory Twin type (3M, Monvrovia, CA) bracket was used to represent a typical conventional ligated bracket and Damon Q (Ormco, Orange, CA) bracket was used to represent a typical passive ligated bracket. Although in the clinical world this represents a good representation of a conventional versus passive bracket, it does introduce variables such as bracket design which have to be considered.

Because brackets were not retested in this experimental design, individual bracket differences due to manufacturer tolerances may introduce some variability in the data.

The data from this experiment allows real quantification in resistance to sliding as a result of perturbations. The limitation is whether and at what point is this data clinically relevant.

3.7 Conclusions

1. Resistance to sliding was statistically significantly different between conventional ligated brackets and passive ligated brackets independent of perturbation level.

2. Perturbations independent of frequency or amplitude had the ability to reduce the resistance to sliding in conventional ligated brackets at both 0 and 6 degrees.

3. High perturbations independent of frequency had a greater reduction in resistance to sliding compared to low perturbations or control in conventional ligated brackets.

4. High perturbation independent of frequency had the ability to reduce the resistance to sliding in passive ligated brackets at 6 degrees (angulation above critical contact angle).

5. Low perturbation independent of frequency was not statistically different from control for resistance to sliding at 6 degrees in passive ligated brackets.

6. Amplitude of perturbations rather than frequency of perturbation play a larger role in reducing the resistance to sliding in both conventional and passive ligated brackets.

7. At an angle above the critical contact angle (6 degrees), high perturbation levels independent from frequency has the ability to reduce resistance to sliding to a greater degree in passive ligated brackets compared to conventional ligated brackets.

8. Perturbations have the ability to reduce resistance to sliding under certain conditions which agrees with existing literature.

Acknowledgement

I would like to thank both Ormco and 3M for their generous donations of brackets and wires for this experiment.

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Chapter 4 – General Discussion

4.1 Final Discussion

Several factors influence the complex phenomenon referred to by Kusy as resistance to sliding. Friction due to ligation force is most influential when $\Theta < \Theta_c$. Ligation force may be influenced by the material used to ligate as well as how tight it is tied in the case of steel ligatures. When Θ_c is achieved at the bracket-archwire interface, friction due to forces between the wire and the slot walls ("binding") and notching begin to play an increasing role in resistance to sliding. Factors which influence binding and notching are the slot size, slot width, and wire size.[1] Slot size and slot width and wire size all have an influence on the contact angle, however wire size may also influence the amount of normal friction that is present along the z axis during tipping movements. For example, smaller diameter wires may "bend" more and the additional flexibility may result in smaller normal frictional force when compared to larger more stiff wires. In orthodontic treatment, due to alignment of the dentition it is rare that a tooth with the bracket slides completely parallel to the archwire as is the case in many of the published studies on friction.[2, 3] Because orthodontic forces are often delivered some distance away from the center of resistance of the tooth, tipping or second order movements are often encountered during sliding mechanics. As the tooth tips against the archwire, contact occurs at the wire-bracket interface to cause some level of binding. It has been postulated that perturbations or vibrations that can occur intra-orally can temporarily release this binding allowing the archwire to slide freely.[4-6] Results from published data all conclude that perturbations can reduce resistance to sliding, however further investigation into the role of perturbation as well as quantification of the change in resistance to sliding have not been complete. At the time of writing, there was no published study on the effect of amplitude and frequency of perturbations on resistance to sliding at differing second order angulations.

This experiment not only allowed us to further validate the claim that perturbations reduce resistance to sliding, but also explores the relationship to a different level. Our findings suggest that the amplitude of the perturbations may play a larger role in reducing resistance to sliding than frequency of the perturbations. We were also able to compare the effect of perturbations on resistance to sliding in two of the typical orthodontic bracket types used in clinical practice (conventional ligated and passive ligated). Lastly we were able to quantify the reduction in resistance to sliding at angles above and below the critical contact angle for both bracket types.

It is always difficult to relate bench research to the clinical setting as in vitro models are often over simplified. Although our findings are statistically significant, there may be some debate on whether it is clinically relevant. As both the frictional measuring device and the perturbation device are both novel designs by the mechanical engineering department at the University of Alberta, results may not be directly compared to other experiments with alternate methodologies and testing equipment.

4.2 Recommendations

Now that we have information regarding the role of perturbations on resistance to sliding in conventional and passive ligated brackets, it may be insightful to introduce state as another variable to better simulate the oral environment. Future research on wet versus dry state on already tested parameters may give more insight and relevance to the in vivo model. Future generations of the frictional device may try to incorporate a periodontal type ligament space to further replicate the intra oral scenario. For reproducibility, future generations of testing devices should have the minimal number of pieces that must be removed and put back for each individual test to minimize possible user errors. For ease of operator use, a software bridge between custom testing software and spreadsheet can be designed as to eliminate the step of transferring data files to enhance efficiency.

4.3 References

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Appendix for Chapters 1, 2, and 3

Appendix A - Search Strategy for Other Databases used for Systematic Review

Scopus Search Strategy

Search Terms and Combination	Results
1. masticat* OR chew* OR bite OR biting OR "bite force"	72321
2. frequen* OR intensity OR force OR pressure OR strength OR duration OR interval OR period	8206990
3. denture* OR removable OR edentulous OR "missing teeth" OR implant* OR partial*	1388333
4. orthodont* OR brace*	62171
5. ((#1 AND #2) AND NOT #3) AND #4	918

Embase OvidSP

Search Terms and Combinations	Results
1. masticat$ OR (explode) mastication OR chew$ OR bite OR biting OR bite force OR (explode) bite	48408
2. frequen$ OR intensity OR force OR pressure OR strength OR duration OR interval OR period	3504903
3. #1 AND #2	12342
4. (explode) denture OR denture$ OR removable OR edentulous OR missing teeth OR implant$ or partial$	769212
5. #3 NOT #4	10743
6. orthodont$ OR brace$ or (explode) orthodontics	47399
7. #5 AND #6	632
8. #7 Limit Human	587

Appendix B – Sample Size determination

For 2x5 Repeated Measures ANOVA we set the effect size to be medium (0.30) and a power = 0.80. Referencing Table C.4 from the Foundations of Clinical Research Applications to Practice textbook we established that sample size needed per group was 27. To build in potential loss due to test failures, 3 additional samples were added to each group resulting in the final n=30 per test condition.

Table referenced from Textbook: Leslie Gross Portney, Mary P. Watkins: Foundations of Clinical Research Applications to Practice 2nd edition, New Jersey, Prentice-Hall Inc; 2000.

Appendix C – Equation for critical contact angle

$$\Theta_c = 57.32 \frac{[1 - \frac{SIZE}{SLOT}]}{\frac{WIDTH}{SLOT}}$$

Where Θ_c = Critical contact angle, SIZE = Archwire size in vertical dimension, SLOT = Bracket Slot Width, WIDTH = Mesial-Distal width of bracket slot. Equation referenced from Kusy.

Kusy RP, Whitley JQ. Influence of archwire and bracket dimensions on sliding mechanics: derivations and determinations of the critical contact angles for binding. European journal of orthodontics. 1999;21(2):199-208

For this experiment an 0.018 x 0.025 Stainless steel archwire was used. Damon Q bracket width referenced by ORMCO to be 0.110” and 3M victory series twin referenced by 3M to be 0.127”.

Appendix D – Pairwise comparisons of brackets and perturbation test groups at 0 degrees and 6 degrees

Post Hoc Pairwise comparison after fixing angulation with ANOVA using SPSS.

Pairwise comparison for Angulation 0 degrees

Dependent Variable:RS0

bracket	(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
						Lower Bound	Upper Bound
1	3	4	.077*	.017	.000	.044	.109
		5	.118*	.017	.000	.085	.150
		6	.367*	.017	.000	.335	.400
		7	.311*	.017	.000	.278	.343
	4	3	-.077*	.017	.000	-.109	-.044
		5	.041*	.017	.014	.008	.073
		6	.290*	.017	.000	.258	.323
		7	.234*	.017	.000	.201	.266
	5	3	-.118*	.017	.000	-.150	-.085
		4	-.041*	.017	.014	-.073	-.008
		6	.250*	.017	.000	.217	.282
		7	.193*	.017	.000	.160	.226
	6	3	-.367*	.017	.000	-.400	-.335
		4	-.290*	.017	.000	-.323	-.258
		5	-.250*	.017	.000	-.282	-.217
		7	-.057*	.017	.001	-.089	-.024
	7	3	-.311*	.017	.000	-.343	-.278
		4	-.234*	.017	.000	-.266	-.201
		5	-.193*	.017	.000	-.226	-.160
		6	.057*	.017	.001	.024	.089
2	3	4	-.004	.017	.792	-.037	.028
		5	.008	.017	.648	-.025	.040
		6	-.043*	.017	.010	-.075	-.010
		7	-.015	.017	.361	-.048	.017
	4	3	.004	.017	.792	-.028	.037
		5	.012	.017	.472	-.021	.044
		6	-.039*	.017	.020	-.071	-.006
		7	-.011	.017	.516	-.043	.022
	5	3	-.008	.017	.648	-.040	.025
		4	-.012	.017	.472	-.044	.021
		6	-.050*	.017	.002	-.083	-.018
		7	-.023	.017	.171	-.055	.010
	6	3	.043*	.017	.010	.010	.075
		4	.039*	.017	.020	.006	.071
		5	.050*	.017	.002	.018	.083
		7	.028	.017	.094	-.005	.060
	7	3	.015	.017	.361	-.017	.048
		4	.011	.017	.516	-.022	.043
		5	.023	.017	.171	-.010	.055
		6	-.028	.017	.094	-.060	.005

Pairwise comparison for Angulation 6 degrees

Dependent Variable:RS6

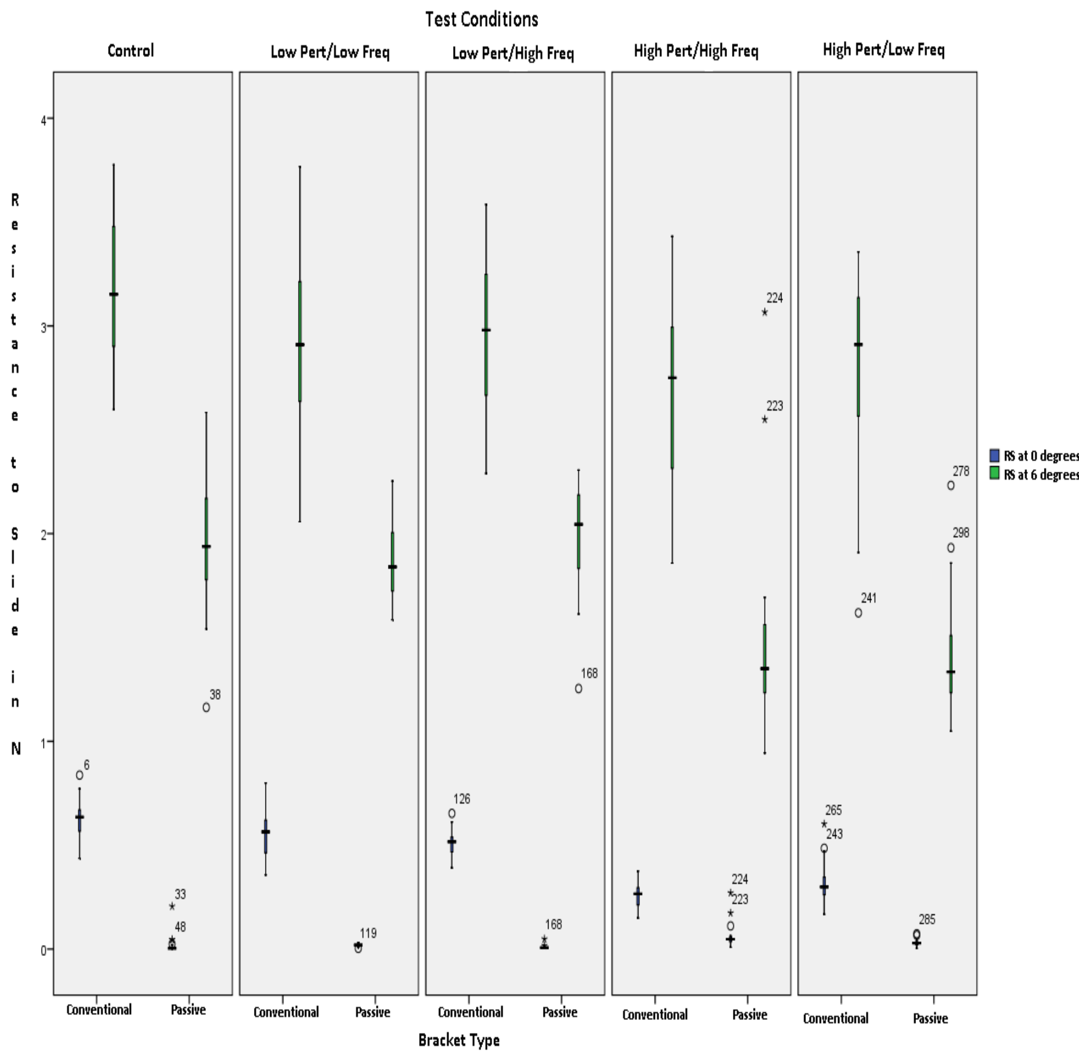
bracket	(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
1	3	4	.290*	.090	.001	.113	.466
		5	.215*	.090	.017	.039	.392
		6	.495*	.090	.000	.319	.672
		7	.381*	.090	.000	.204	.557
	4	3	-.290*	.090	.001	-.466	-.113
		5	-.074	.090	.407	-.251	.102
		6	.206*	.090	.022	.029	.382
		7	.091	.090	.312	-.086	.267
	5	3	-.215*	.090	.017	-.392	-.039
		4	.074	.090	.407	-.102	.251
		6	.280*	.090	.002	.104	.456
		7	.165	.090	.066	-.011	.341
	6	3	-.495*	.090	.000	-.672	-.319
		4	-.206*	.090	.022	-.382	-.029
		5	-.280*	.090	.002	-.456	-.104
		7	-.115	.090	.201	-.291	.062
	7	3	-.381*	.090	.000	-.557	-.204
		4	-.091	.090	.312	-.267	.086
		5	-.165	.090	.066	-.341	.011
		6	.115	.090	.201	-.062	.291
2	3	4	.108	.090	.229	-.068	.284
		5	-.009	.090	.924	-.185	.168
		6	.526*	.090	.000	.350	.702
		7	.569*	.090	.000	.393	.745
	4	3	-.108	.090	.229	-.284	.068
		5	-.117	.090	.194	-.293	.060
		6	.418*	.090	.000	.242	.594
		7	.461*	.090	.000	.285	.637
	5	3	.009	.090	.924	-.168	.185
		4	.117	.090	.194	-.060	.293
		6	.534*	.090	.000	.358	.711
		7	.578*	.090	.000	.401	.754
	6	3	-.526*	.090	.000	-.702	-.350
		4	-.418*	.090	.000	-.594	-.242
		5	-.534*	.090	.000	-.711	-.358
		7	.043	.090	.631	-.133	.219
	7	3	-.569*	.090	.000	-.745	-.393
		4	-.461*	.090	.000	-.637	-.285
		5	-.578*	.090	.000	-.754	-.401
		6	-.043	.090	.631	-.219	.133

Bracket 1 = Conventional Ligated Bracket, Bracket 2 = Passive Ligated Bracket

Condition 3 = Control, Condition 4 = Low perturbation/Low Frequency, Condition 5 = Low Perturbation/High Frequency, Condition 6 = High Perturbation/High Frequency, Condition 7 = High Perturbation/Low Frequency

Outputs copied directly from SPSS outputs.

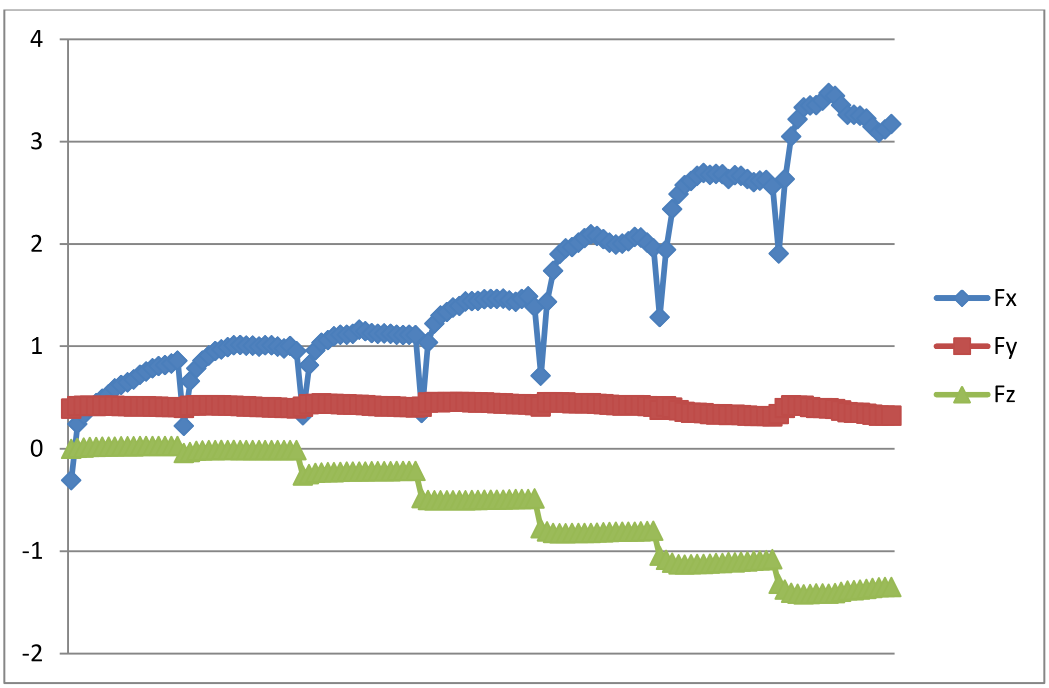
Appendix E – Boxplots of Bracket Type and Test Conditions at 0 and 6 degrees



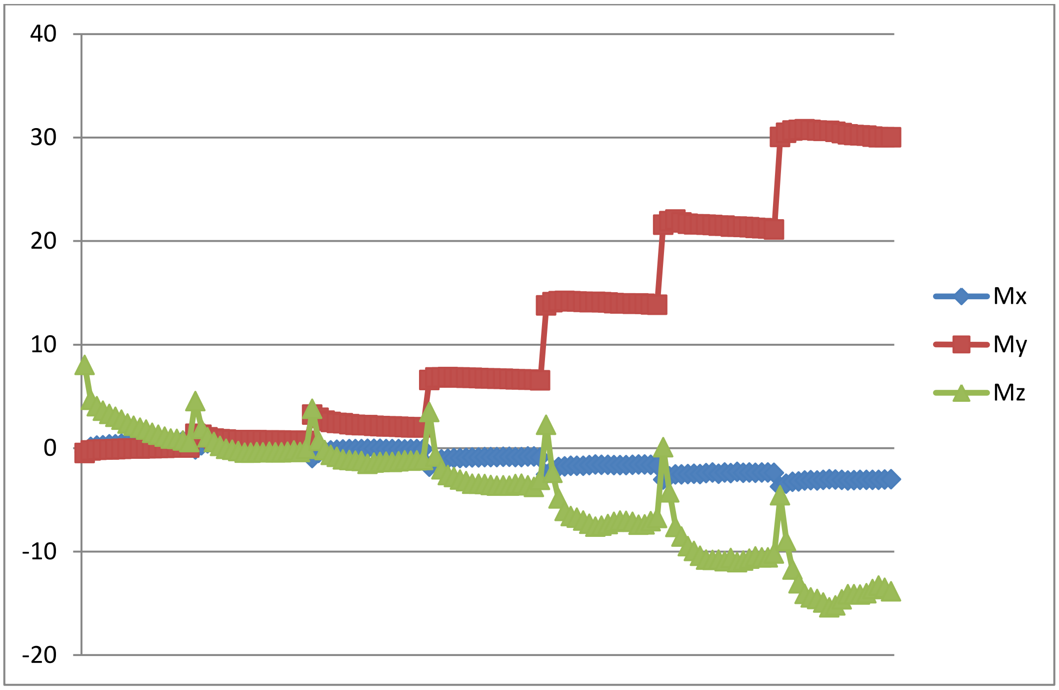
Appendix F – Raw Data transformed to the level of the bracket for forces in x,y, and z axis (Fx, Fy, and Fz), Moments in x, y, and z axis (Mx, My, Mz), and resistance to sliding (RS)

The following line graphs represent the raw data output that has been transformed to the level of the bracket. Graphs represent the forces in the X, Y, and Z planes of space (Fx, Fy, and Fz), as well as the associated moments Mx, My, and Mz. The third graph in each set represents the Resistance to Sliding (RS) value, which as previously described represents the resultant vector of Fx and Fz. Each individual data point represents the average of 500 samples. Sampling rate was tested at 4000Hz which converts to 8 samples per second. Graphically the x-axis represents time and the y-axis represents the force in Newtons.

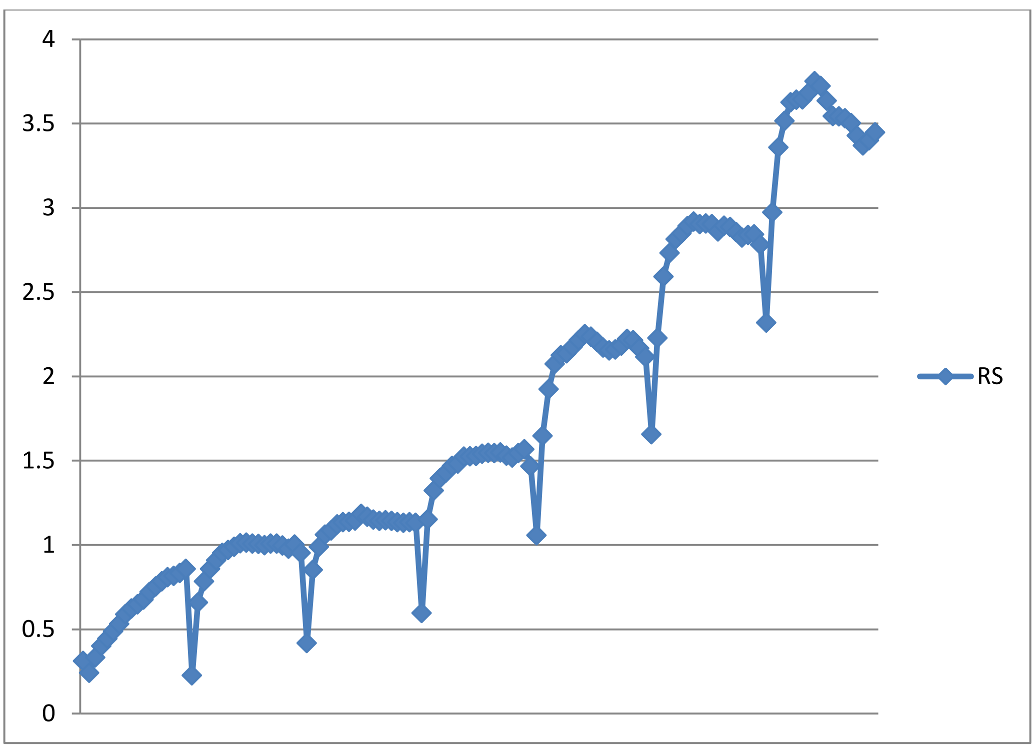
Sample conventional ligated (3M) bracket for control test condition:



Graph of Forces in x,y, and z axis at the level of the bracket.

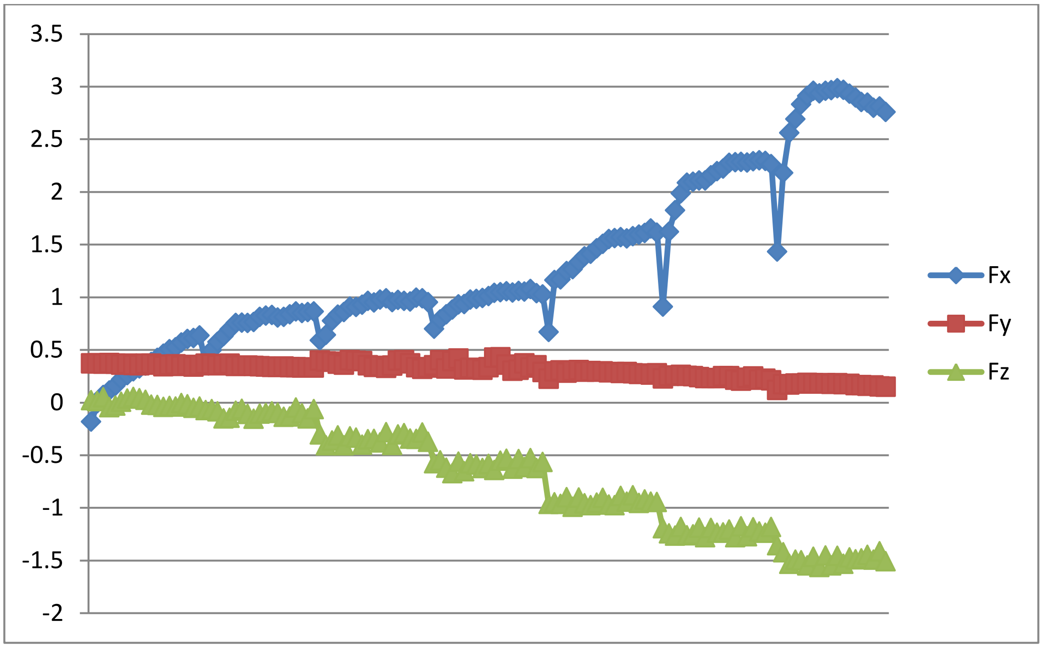


Graph of Moments in x, y, and z axis at the level of the bracket.

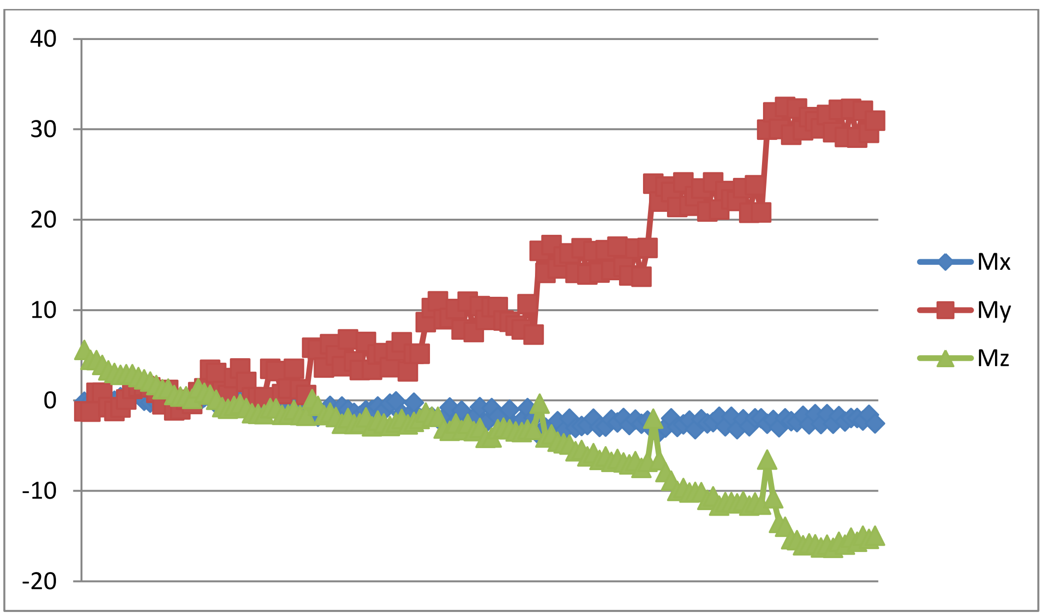


Graph of the resistance to sliding (RS) at the level of the bracket

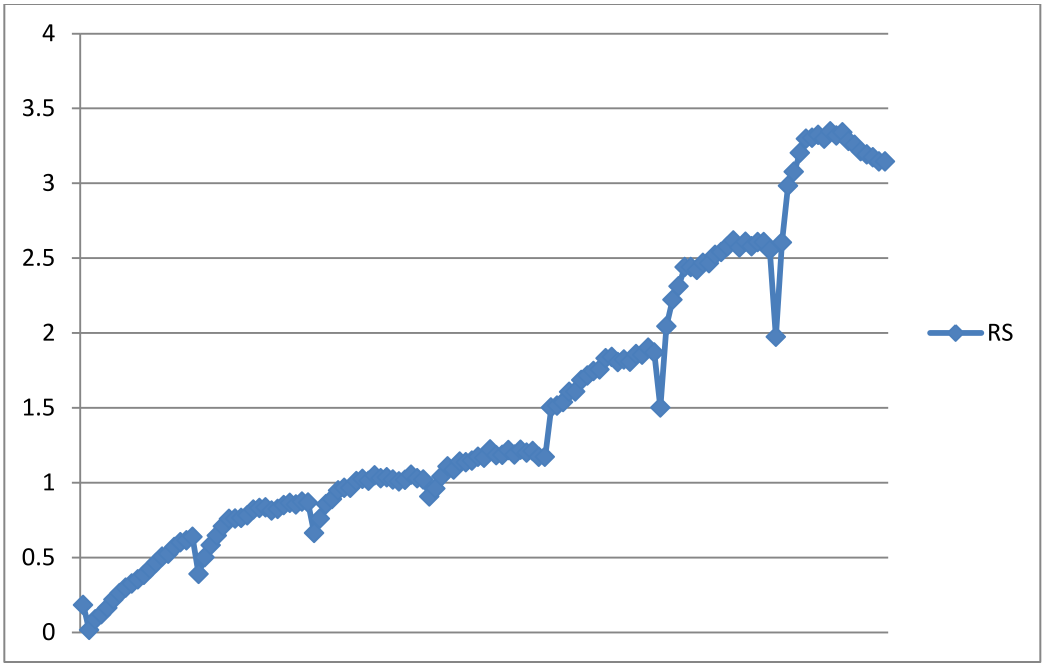
Sample conventional ligated (3M) bracket under high perturbation / high frequency test condition:



Graph of Forces in x, y, and z axis at the level of the bracket.

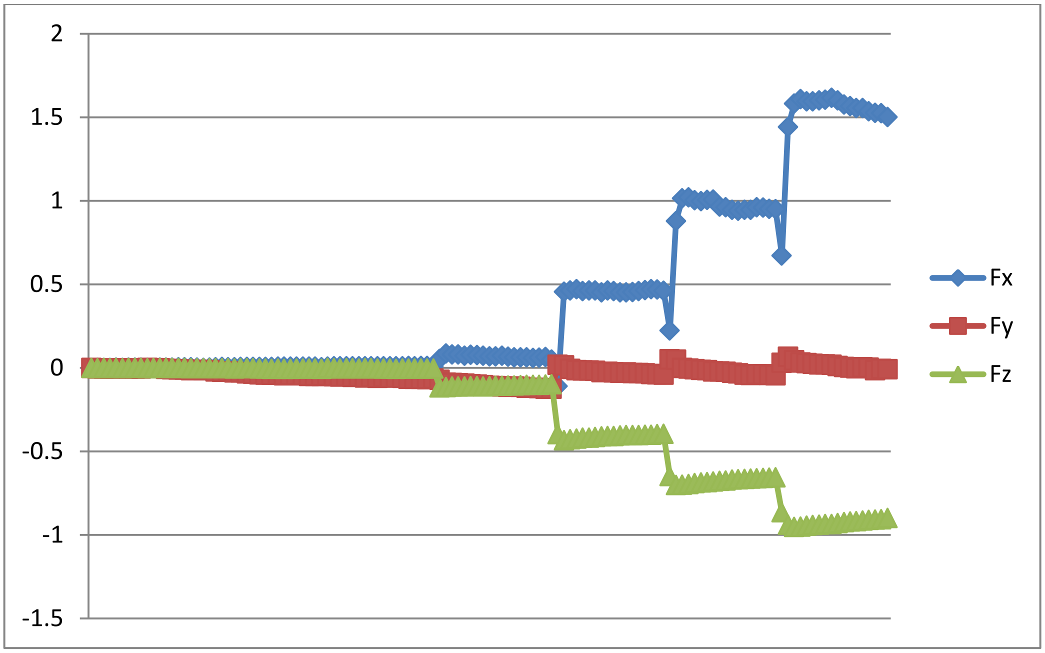


Graph of Moments in x, y, and z axis at the level of the bracket.

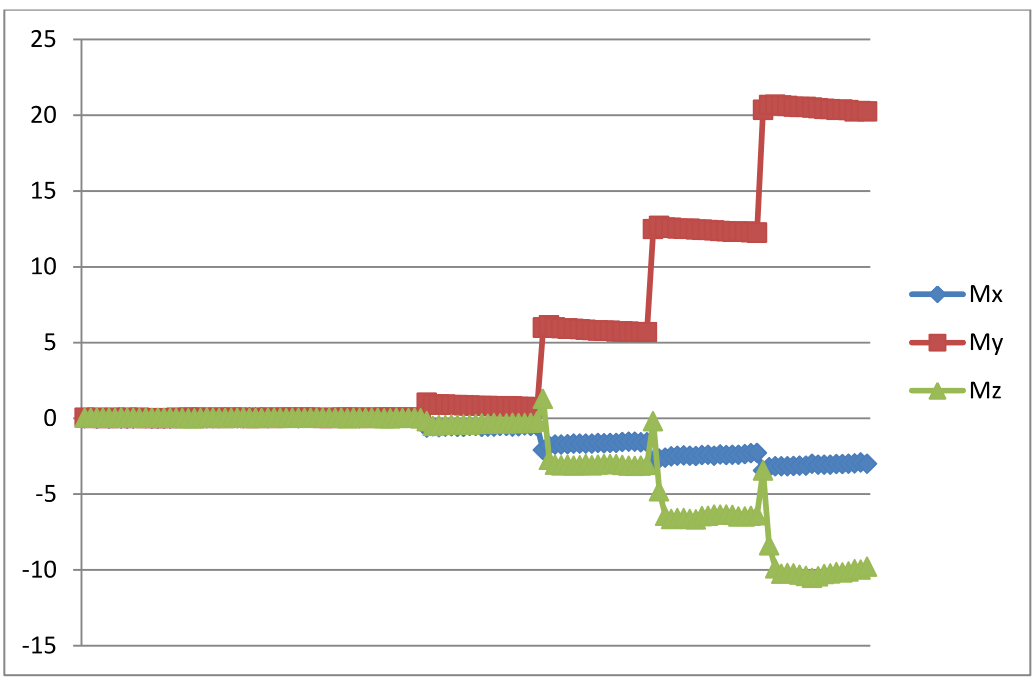


Graph of the Resistance to Sliding (RS) at the level of the bracket.

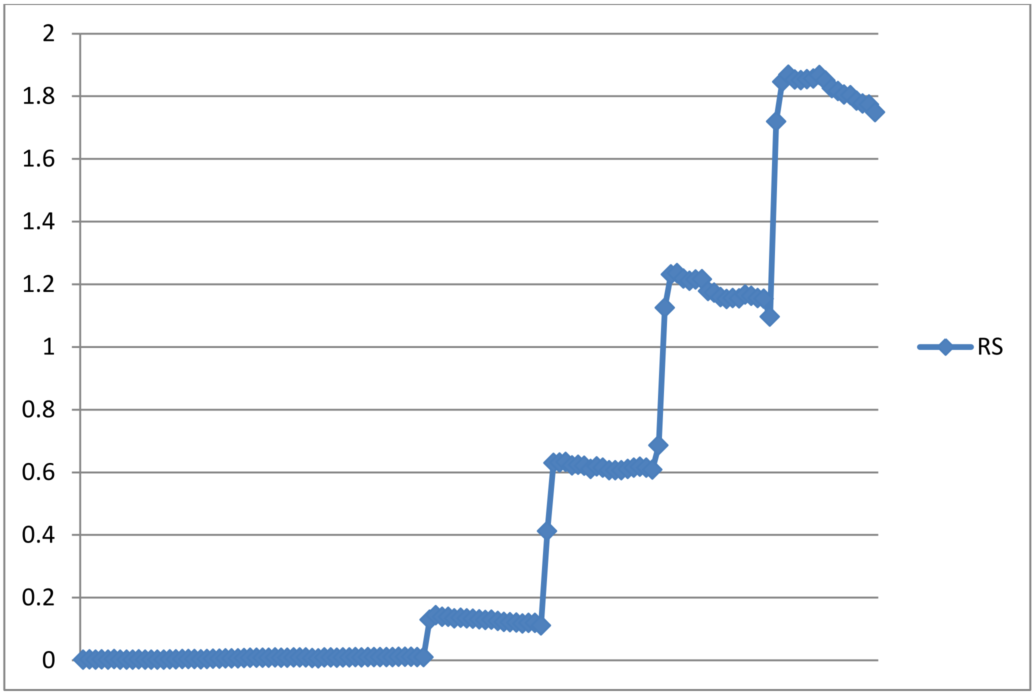
Sample passive ligated (Damon) bracket for control test condition:



Graph of Forces in x, y, and z axis at the level of the bracket.

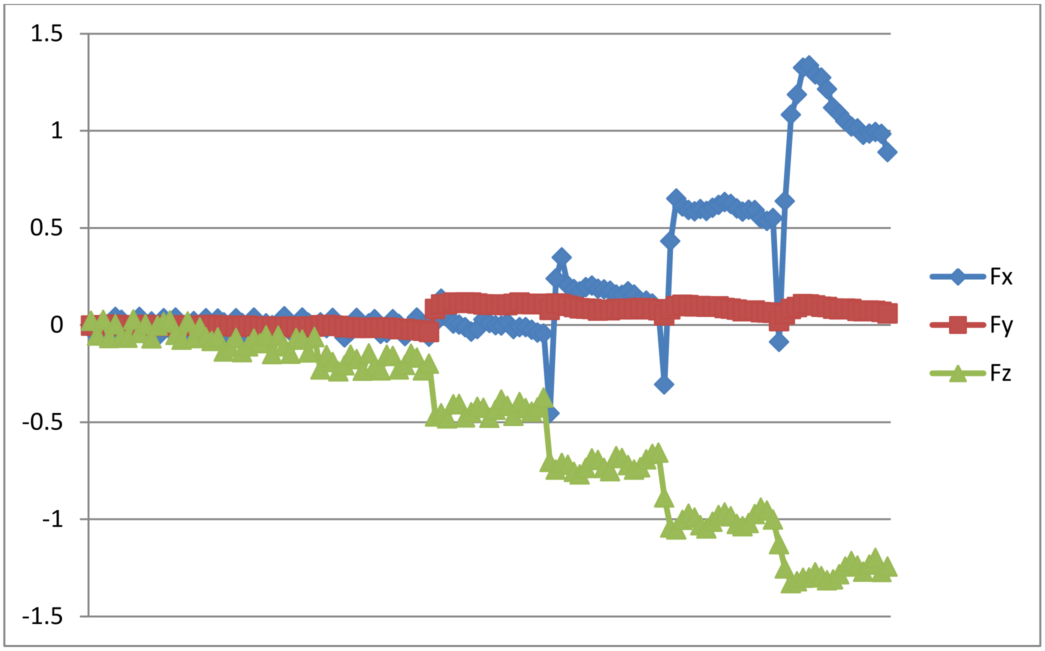


Graph of Moments in x, y, and z axis at the level of the bracket.

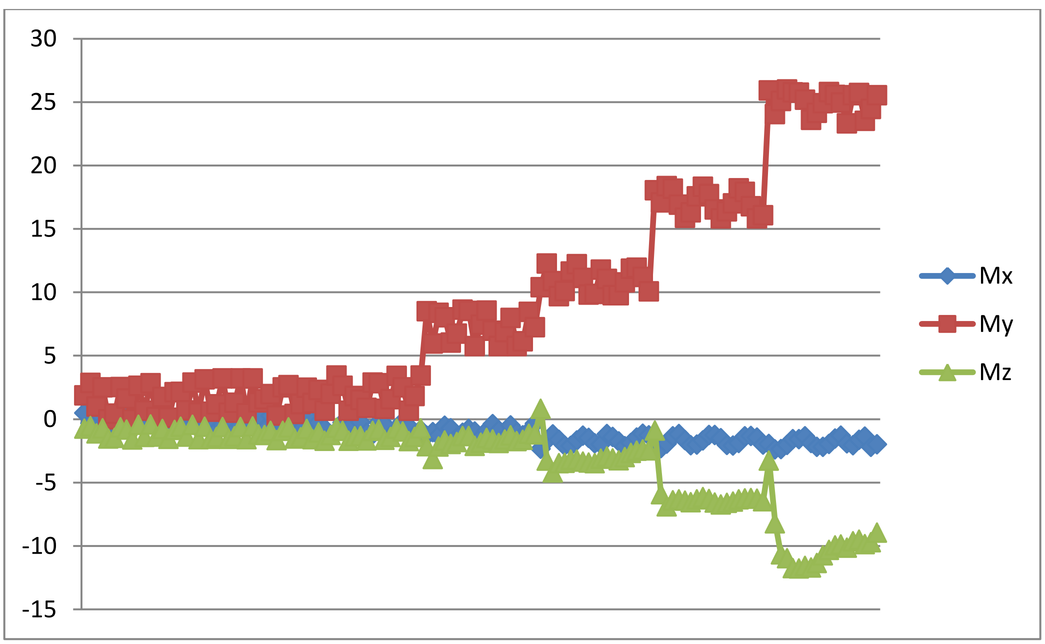


Graph of the Resistance to Sliding (RS) at the level of the bracket

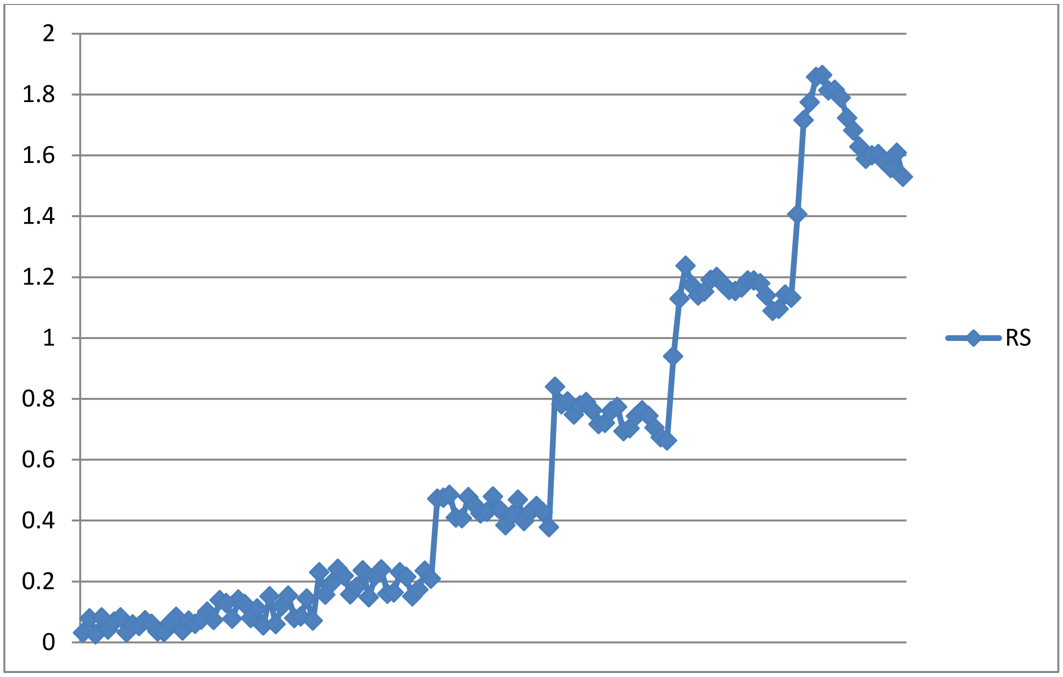
Sample passive ligated (Damon) bracket for high perturbation / high frequency test condition:



Graph of Forces in x, y, and z axis at the level of the bracket.



Graph of Moments in x,y, and z axis at the level of the bracket.



Graph of Resistance to Sliding (RS) at the level of the bracket.