THE EFFECT OF ARCHWIRE VIBRATIONS ON THE STICK-SLIP BEHAVIOR

OF THE BRACKET-ARCHWIRE INTERFACE UTILIZING

CLINICALLY RELEVANT TIPPING MOMENTS

A THESIS IN
Oral Biology

Presented to the Faculty of the University
of Missouri-Kansas City in partial fulfillment of
the requirements for the degree

MASTER OF SCIENCE

by
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Kansas City, Missouri
2011

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ABSTRACT

This study evaluated bracket-archwire frictional resistance as a function of ligation method and archwire vibration. In vivo archwire vibrations were measured to obtain frequencies and amplitudes for ex vivo testing. Active and passive ligation methods were compared for 9 vibration scenarios utilizing a friction testing apparatus, where a nickel titanium spring was attached to a wire bonded to an upper right canine bracket to create a 1500 cN-mm moment. As retraction forces were applied, the amount of time (ln, s) for each bracket configuration to move along a stainless steel wire was recorded in 90 trials. Results indicated that trials containing medium (150mV) and high (190mV) amplitude vibrations had significantly less friction, 4.81 ± 2.08 and 4.67 ± 2.00, respectively, than those subjected to low (110mV) amplitudes, 5.80 ± 1.39 ($p=0.04$). There were no significant differences between passive and active ligation methods ($p=0.100$) and frequency of vibrations ($p=0.317$) on bracket-archwire frictional resistance.

The undersigned, appointed by the Dean of the School of Dentistry, have examined a thesis titled "The Effect of Archwire Vibrations on the Stick-Slip Behavior of the Bracket-Archwire Interface Utilizing Clinically Relevant Tipping Moments," presented by Julie Elizabeth Olson, candidate for the Master of Science degree, and hereby certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

INTRODUCTION

Friction has been a widely discussed topic in the field of orthodontics for many years.

Recently, much effort has been applied to decrease frictional resistance involved in

orthodontic sliding mechanics. This technique used during orthodontic treatment is one in

which teeth are moved by virtue of the attached brackets' abilities to slide along the archwire

when pulled or pushed by a device, such as a spring. The tooth's ability to move is strongly

determined by the amount of friction between the bracket and archwire. In contrast,

alternative techniques to move teeth, utilizing loops and various bends in the archwire,

require high amounts of friction. With these mechanics, unlike sliding mechanics, it is

advantageous for high amounts of friction to occur between the bracket and archwire because

teeth move with the archwire as opposed to along the archwire. The scope of this research

will focus on sliding mechanics, in which low friction is desired. More specifically, the

mechanics and friction associated with canine retraction will be investigated.

Clinicians and manufacturers have worked diligently to minimize friction at the

bracket-archwire interface by virtue of archwire material, ligation method, and innovative

bracket design. Since the beginning of the 1980s, there has been a surge in the number of

self-ligating, ligature free, brackets (Harradine 2003). At present, market demands are

continually forcing manufacturers to redesign their bracket ligation apparatus to maintain an

edge on the competition.

The increasing number of in vitro studies on these newly designed brackets has led to

much discussion over which bracket design provides the utmost friction reduction. Frictional

resistance at the bracket-archwire interface has been studied at great lengths, comparing various self-ligating brackets, as well as, self-ligating to conventional ligation methods (Drescher et al. 1989; Cacciafesta et al. 2003; Tecco et al. 2007). However, investigations have essentially used steady state models (Braun et al. 1999). Little attention has been given to minor perturbations due to forces of mastication and the effects on the stick-slip behavior at the bracket-archwire interface. As a result, steady state studies may overestimate the amount of clinical friction involved in sliding mechanics (O'Reilly et al. 1999).

As noted by Swartz in 2007, "additional studies that focus on the dynamic oral environment are needed to determine the true influence of friction in orthodontic treatment." Previous ex vivo studies that have attempted to simulate minor perturbations have shown a decrease in friction (Braun et al. 1999; O'Reilly et al. 1999). However, the use of arbitrary amounts of vibration in these studies indicates a need for more clinically applicable values. In vivo measurements of archwire vibration during human mastication are needed to apply during ex vivo friction testing. Using clinically relevant archwire vibrations will create ex vivo friction studies that are more pertinent to patient treatment scenarios. The literature suggests that no researchers have ever investigated this phenomenon.

Friction

Classic Friction

Friction is the force that resists the relative motion of two objects in contact and its direction is tangential to the interface of the two surfaces. There are two types of friction, static and kinetic. Static friction is the smallest force needed to start motion while kinetic friction is the force needed to continue motion. Friction is an integral part of sliding mechanics in orthodontics. During sliding mechanics, the biologic tissues respond, and tooth movement occurs only when the forces applied exceed the friction at the bracket-archwire interface (Nishio et al. 2004). The magnitude of friction is a product of the normal (perpendicular) force component and the coefficient of friction of the materials in contact. Thus, when attempting to move teeth using sliding mechanics, friction can be a burden to orthodontists. In other clinical situations, when constraint of sliding movements between the archwire and bracket are desired, friction is an asset.

Normal Force

The normal force is the force component which acts perpendicularly to the direction of desired movement. For example, when an archwire is engaged in a bracket slot and ligated in place, normal (perpendicular) forces potentially exist between the wire and the occlusal, gingival, and lingual surfaces of the bracket slot; between the ligature and the archwire; and also, differentially at the mesial and distal edges of the bracket in situations when the bracket is tipped and/or rotated. It has been demonstrated that elastomeric ligation produces the highest normal force, followed by stainless steel ties and self-ligating mechanisms (Bednar et al. 1991; Shivapuja and Berger 1994; Iwasaki et al. 2003; Krishnan

et al. 2009). It is for this reason that manufacturers continue to develop self-ligating designs to decrease the normal force exerted on the archwire and resultant friction during sliding mechanics. A substantial reduction in frictional resistance was noted when elastomeric ligation was compared to passive and active self-ligation, a decrease of 75% and 50% respectively (Krishnan et al. 2009). In addition, differences in normal force magnitudes between tight and loose stainless steel ligation have been shown to be significant (Iwasaki et al. 2003). That is, the normal forces created during wire ligation varied amongst clinicians, as well as, on successive attempts by the same clinician (Iwasaki et al. 2003).

Coefficient of Friction

In addition to the normal force, the coefficient of friction contributes to overall frictional resistance. The coefficient of friction is a dimensionless ratio of the force of friction between two bodies and the force pressing them together, the normal force. Changing opposing materials can therefore increase or decrease the coefficient of friction, in turn influencing frictional resistance (Kusy 2002). A good example is archwire selection. Three different archwire types are typically used in orthodontics; stainless steel, nickel-titanium, and titanium-molybdenum alloy (TMA) (Proffit et al. 2007). A recent study reported that frictional resistance increased in the order of stainless steel, nickel-titanium, and titanium-molybdenum alloy (Krishnan et al. 2009). These findings agree with other studies (Drescher et al. 1989; Sims et al. 1993; Cacciafesta et al. 2003). It is thought that the high amount of titanium in the TMA wire influences the surface reactivity causing adherence during sliding mechanics (Krishnan et al. 2009). Via scanning electron microscopy,

titanium-molybdenum alloy wires showed an extensive surface roughness in comparison to stainless steel and nickel titanium (Drescher et al. 1989).

Bracket-Archwire Stick-Slip Behavior

When the bracket slot and archwire are parallel, the resistance to sliding between the bracket and archwire is affected by classic friction which includes the normal force and coefficient of friction (Articolo and Kusy 1999). With a parallel configuration, the contact angle between the bracket slot and the archwire is 0 degrees (Fig. 1A, B), and the wire can be passed through the bracket slot with minimal contact. In clinical situations of canine retraction, a contact angle of 0 degrees rarely exists between the bracket slot and archwire. Further contributions to sliding resistance arise once the components move and bracket slot and archwire are no longer exactly parallel to one another.

As retraction forces are applied to the tooth via the orthodontic attachment on the vestibular surface of the crown, distal crown tipping and distolingual rotation almost always occur so that the bracket slot and archwire surfaces are no longer parallel, and the mesial and distal edges of the bracket contact the archwire creating an increased contact angle (Fig. 1C). Friction goes up proportionally as the contact angle increases (Nishio et al. 2004). Then binding of the archwire with the edges of the bracket and notching can subsequently occur on the archwire, which results in the "stick" phenomenon. Whereas, the ability of the wire to release from this bound configuration with the edge of the bracket illustrates the "slip" phenomenon. This stick-slip phenomenon occurs in clinical situations in which a tooth is retracted by an orthodontic attachment located any distance away from the tooth's center of resistance which leads to tipping or rotation of the tooth.

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Several studies have investigated the effects of increased bracket slot-archwire contact angles on archwire binding and frictional resistance during simulated tooth movement. When five bracket slot-archwire contact angles were studied, it was found that archwire binding became greater as the contact angle increased. A contact angle of 3 degrees had a binding influence of 73% of the frictional resistance while 7 degrees had a binding influence of 94% (Articolo and Kusy 1999).

Practitioners have attempted many ways to curtail frictional resistance that results from classic friction, as well as, investigate ways to reduce bracket-archwire binding. A number of considerations factor into decisions regarding sliding mechanics in orthodontics. These factors include, but are not limited to, archwire selection and bracket-archwire contact angle, discussed previously, as well as, ligation method and bracket design.
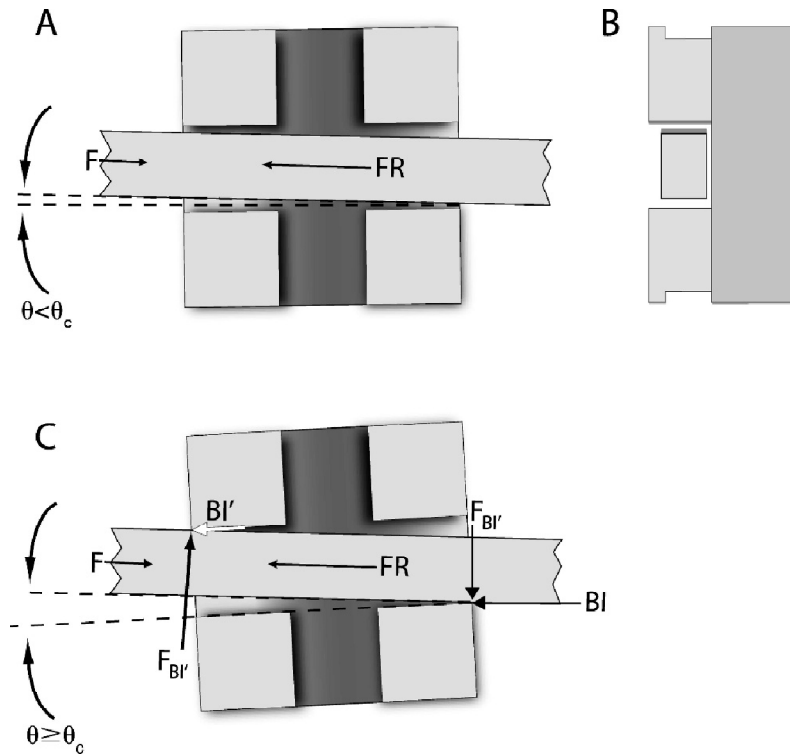
Fig. 1. Stick-slip bracket model. A. Bracket-archwire combination demonstrating a passive state between the bracket slot and archwire. The contact angle (θ) is less than the critical contact angle (θ_c). B. Side view showing the passive state of the archwire, in which no components are touching the bracket slot. Clinically, this situation would never occur. C. When the bracket-archwire relationship changes to an active binding configuration, the contact angle (θ) becomes greater than the critical contact angle (θ_c). (F = force, FR = friction, BI = binding, F_{BI} = the force of binding) (Burrow 2010)

Bracket Ligation

Bracket ligation is a crucial concept during orthodontic treatment. It must ensure full bracket engagement of the archwire, exhibit low friction between the bracket and archwire during some applied techniques such as sliding mechanics, and permit high friction when constraint of the bracket-archwire relationship is desired. The desire to obtain ideal ligation for the particular orthodontic situation has led to several new bracket designs over the years, from traditional edgewise to modern self-ligating. Conventional twin brackets, utilizing either an elastomeric or stainless steel ligature, have been a popular fixed appliance system used for most of the 20th century. Therefore, it is important to evaluate conventional ligation as a standard to compare various methods of ligation.

Conventional Elastomeric and Stainless Steel Ligation

When considering the keys to ideal ligation for sliding mechanics, conventional ligation using either elastomeric or stainless steel ties has been shown to have many shortcomings. Friction associated with elastomerics is nearly 30 to 50 percent greater than that associated with stainless steel ties and self-ligating mechanisms (Shivapuja and Berger 1994). Further, force decay of elastomerics has been well documented (Harradine 2003). Experimental studies have demonstrated a rapid force loss of 53 to 64% in 24 hours (Taloumis et al. 1997). In addition, elastomeric ligatures lose dimensional stability and decrease force levels when exposed to moisture and heat. These undesirable properties create insufficient engagement of the archwire and loss of tooth control (Taloumis et al. 1997).

Unlike elastomeric ligatures, loosely tied stainless steel ligatures have shown negligible friction in both wet and dry states (Hain et al. 2003). This potentially minimizes frictional resistance to sliding brackets along the archwire. However, as mentioned prior, there is great variance in tightness of wire ligation amongst clinicians, despite intent to tie loosely or tightly, creating an unpredictable situation (Iwasaki et al. 2003). In addition, ligation with stainless steel ties has been shown to add almost twelve minutes of time to remove and place two archwires (Shivapuja and Berger 1994). This inconvenience is largely why few clinicians use wire ties as their primary ligation method.

<div align="center">Self-Ligating Mechanisms</div>

An alternative to conventional ligation methods is the self-ligating mechanism. As of late, the prevalence of self-ligating brackets has increased in the orthodontic market (Harradine 2003; Rinchuse and Miles 2007). Self-ligating brackets are ligatureless bracket systems with a mechanical device to hold the archwire into the edgewise slot (Cacciafesta et al. 2003).

Most often referred to as one group, self-ligating brackets are actually quite dichotomous. These brackets can more accurately be divided into passive and active mechanisms. Passive self-ligating brackets have a clip or door that does not, theoretically, press against the archwire, while active self-ligating designs contain a spring clip that makes positive contact with the archwire (Rinchuse and Miles 2007; Krishnan et al. 2009). Conventional ligation methods, using elastomeric ties, are considered active due to the normal force on the archwire actively engaging the wire into the slot at all times. Mechanical properties and examples of passive and active self-ligating designs are discussed below.

<div align="center">9</div>

Passive Self-Ligation

One passive mechanism involves a labial slide that opens and closes vertically forming a tube inside the bracket. This tube design creates a vestibular surface with no ability to invade the slot (Harradine 2003). An alternative passive design utilizes two nickel-titanium clips which open and close automatically through elastic deformation as the archwire is engaged. This passive appliance consists of a mesh base, bracket body, and two clips held on by mechanical means (Trevisi 2007). The use of nickel-titanium clips may influence the resistance to movement of the archwire as the coefficient of friction of nickel-titanium has been shown to be larger than both cobalt-chromium and stainless steel used in other self-ligating systems (Budd et al. 2008). Further studies are needed to investigate this property.

Active Self-Ligation

Active self-ligating brackets have a much more versatile design than passive self-ligating brackets. Active brackets contain a spring clip that reduces the slot size in the horizontal dimension creating a smaller interior gingival wall relative to the incisal/occlusal wall (Rinchuse and Miles 2007). For example, in one active self-ligating bracket system, the horizontal gingival wall measures 0.0195 inches while the occlusal horizontal wall is 0.0285 inches. As larger wires are used, the action of the bracket spring clip increases (Harradine 2003). With increasing wire sizes, this bracket design would theoretically exhibit higher frictional forces than passive self-ligating designs. Frictional differences between active and passive self-ligation utilizing various wire dimensions have been demonstrated in several steady state bench top experiments discussed below (Budd et al. 2008; Krishnan et al. 2009).

Friction Studies

Steady-State Bench Top Studies

Studies involving frictional forces between brackets and archwires are numerous, ranging from steady-state models to attempts at replicating the unique oral environment. A popular experimental set-up draws a straight archwire through the bracket slot at various speeds and loads using a universal testing machine (Shivapuja and Berger 1994; Cacciafesta et al. 2003; Nishio et al. 2004; Franchi et al. 2008). In one example, utilizing a cantilever apparatus, an archwire was pulled through various bracket types at a speed of 0.001 inch per minute with a full scale load of one pound (528 cN). In this study, along with many others, an artificial salivary medium was also used (Ho and West 1991; Kusy et al. 1991; Shivapuja and Berger 1994; Kusy 2002). The conflicting outcomes of these studies have led to the questionable role of artificial saliva on frictional resistance in vitro. For this reason, artificial salivary mediums will not be used in the current study.

Various bracket-archwire contact angles have also been considered during in vitro frictional studies (Sims et al. 1993; Articolo and Kusy 1999; Braun et al. 1999; Nishio et al. 2004; Budd et al. 2008), allowing clinical crown tipping to be simulated (Burrow 2009). It is conclusive amongst these studies, as bracket slot angulations relative to the archwire increase, so does the frictional resistance at the bracket-archwire interface (Articolo and Kusy 1999; Braun et al. 1999; Thorstenson and Kusy 2002; Nishio et al. 2004). It is evident that incorporating a clinically relevant tipping moment in vitro better simulates the biomechanical phenomenon of tooth movement.

Although varying research designs have been used, most in vitro studies agree that static and kinetic frictional forces are lower in passive self-ligating compared to active self-ligating brackets, with conventional brackets having the highest frictional resistance (Sims et al. 1993; Shivapuja and Berger 1994; Articolo and Kusy 1999; Tecco et al. 2007; Budd et al. 2008; Franchi et al. 2008; Krishnan et al. 2009). However, further studies are needed to analyze how various bracket designs are affected by the dynamic oral environment.

Friction Studies Involving Vibrational Energy

It was as early as 1970 when Hixon recognized the effect of human mastication in reducing bracket-archwire friction. When evaluating force delivery and tooth movement during this study, the wire slid more easily when subjected to oral forces from mastication (Hixon et al. 1970). Despite this, most in vitro friction studies fail to include vibrational energy associated with mastication and its potential effect on archwire frictional resistance. Further, in vivo studies that measure the vibrational energy at the bracket-archwire interface created during mastication are rare.

The small numbers of in vitro studies that have incorporated vibrations at the bracket-archwire interface agree that steady-state models over estimate the impact of friction (Braun et al. 1999; O'Reilly et al. 1999). In a previous thesis project, Liew (1993) placed oscillating forces of 25 to 400 cN at 90 Hz on the archwire as it was drawn through a bracket. This in turn reduced sliding resistance by 60% with 25 cN of wire displacement force and 85% with 100 cN displacement (Swartz 2007). Another study utilized finger perturbations in three planes of space to simulate vibration of the archwire (Braun et al. 1999). A mean force of 87.2 cN was used, resulting in kinetic frictional resistance reducing to zero in 95.8% of the

experiments conducted (Braun et al. 1999). These perturbations were an inexact replica of the intraoral environment.

One published study used a clinically relevant frequency of 81 cycles per minute, based on reported values for normal chewing. Although a clinically applicable frequency was used, amplitudes of 0, 0.25, 0.5, and 1.0 mm of wire displacement were chosen by this author. Results found a linear relationship between displacement and friction (O'Reilly et al. 1999).   To date, there are no studies in the literature that have ever incorporated clinically measured frequencies and amplitudes for both test values. At least one or both of these values were chosen at random in all previous experiments. No quantitative data are currently available regarding the levels of vibration associated with human mastication in individuals undergoing orthodontic treatment. Further research is needed to quantify intraoral vibrational energy at the bracket archwire interface in order to replicate the dynamic oral environment in vitro.

Measurements of Mastication Parameters

The effect of mastication on the dentition has been largely studied in other dental specialties. A wide range of studies have focused on the loading of the dentition during human mastication in terms of frequency and force. It has been estimated that teeth undergo approximately 10^6 chewing cycles annually which averages to about 2700 daily tooth to tooth contacts and a loading rate of 0.5 to 3 Hz (Yurkstas 1965). An average of approximately 9 minutes of total chewing forces occur per day with each stroke lasting 0.3 seconds (Graf 1969).

In addition to chewing frequency, magnitudes of chewing forces in dentate subjects have been well documented. Force values are most often presented as either kilograms or Newtons. Although these values are strongly dependent on the food or non-edible substance used; a range of 4.6 to 9.0 kg has been reported (Neill et al. 1989). A kilogram is an inaccurate representation of mastication force as it is a measure of mass rather than force. Stress values in megapascals (MPa) have also been used to report loads during mastication. A maximum contact stress during chewing has been reported as 20 MPa (Brunski 1988). The unit, MPa, is a more accurate measure of mastication forces because it is a measure of force per unit area, defined as one Newton per square meter.

Although human chewing has been well reported in the dental field, more studies in orthodontics are needed to measure quantitatively the effect of masticatory force on the stick-slip behavior along the archwire. Mastication is an uncontrollable variable of orthodontic treatment. Accurately understanding the force needed to overcome frictional resistance allows for more optimal mechanics and hopefully more predictable tooth movement. A more thorough evaluation of the dynamic oral environment should be considered when orthodontic tooth retraction and sliding mechanics are to be done.

Problem Statement

Presently, there are no quantitative data available regarding the levels of archwire vibration associated with human mastication in individuals undergoing orthodontic treatment. Further, very little published research has investigated the influence of archwire vibrations on bracket-archwire frictional resistance. The purpose of this study was to obtain in vivo measurements of frequency and amplitude associated with oral disturbances on orthodontic appliances. Clinically measured archwire vibrations were then replicated ex vivo to evaluate the stick-slip behavior at the bracket-archwire interface utilizing clinically relevant tipping moments. Frictional resistances of active and passive bracket ligation were then compared at all vibration scenarios.

Hypothesis

There will be a differential effect of ligation method on bracket-archwire frictional resistance and this effect will differ by frequency and amplitude of archwire vibration.

CHAPTER 2

MATERIALS AND METHODS

The design of this study was two-fold, consisting of both in vivo and ex vivo

components. In vivo measurements of frequency and amplitude were collected as a measure

of archwire vibration that occurs during mastication. The data were then used to establish a

range of clinically relevant frequencies and amplitudes to be applied during ex vivo testing.

Frictional properties of commercially available orthodontic brackets were then compared

under clinically relevant tipping and vibrations.

In Vivo Measurement of Mechanical Vibration

In order to estimate clinically relevant vibrational characteristics, six individuals

participated in the pilot study. The protocol was approved by the UMKC Institutional

Review Board and informed consent was obtained from all participants (Appendix A). The

recruited subjects met the following criteria: currently undergoing treatment in the UMKC

graduate orthodontic clinic, fixed appliances on the maxillary and mandibular anterior and

posterior teeth, the presence of the upper right canine, at least 18 years of age, and

willingness to participate. Patients with tooth or jaw pain or difficulty chewing, those unable

to tolerate biting into raw carrots, and those unable to meet the inclusion criteria were

excluded from the study.

Each subject attended two sessions, approximately two weeks apart. During each

visit, a single axis piezoresistive accelerometer[1] was attached to the upper right canine

bracket and archwire in the occlusogingival direction. The accelerometer was tied with

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[1] Model 4374, Bruel & Kjaer, 2815 A Colonnades Court, Norcross, GA 30071

0.010 inch diameter stainless steel ligature wire. Weighing 0.65 g, the accelerometer was comfortable for the subject while incising. The sensitivity of the accelerometer was expressed in terms of charge per unit acceleration and had a value of 0.26 mV/g. In addition, the range of frequencies that could be measured spanned from 1 to 26,000 Hz.

The subjects were instructed to bite into a rectangular raw carrot sample with dimensions of 30 mm x 10 mm x 10 mm. The length of the carrot sample was oriented parallel to the occlusal plane between the right upper and lower incisors. Subjects incised the carrot by taking a single bite into the 10 mm x 10 mm dimension of the carrot. During each session, 5 bites were completed using a new standardized carrot sample for each bite. Maximum peak-to-peak amplitude (mV) and frequency (Hz) of vibrations along the occlusogingival axis of the maxillary right canine were recorded. Analysis of signal amplitude and frequency was made possible using a digital storage oscilloscope[2].

A range of clinically relevant archwire vibration characteristics was established. The average vibration frequency value was 98.29 Hz (SD $\pm$ 41.19). Two additional frequency values, 139.48 Hz and 57.7 Hz, were calculated by adding and subtracting one standard deviation to and from the mean, respectively. Vibration signals had average peak to peak amplitudes of 151.33 mV (SD $\pm$ 39.22). Two additional amplitude values, 190.55 mV and 112.11 mV, were similarly determined by adding and subtracting one standard deviation to and from the mean, respectively. Each of the three frequencies was combined with each of the three amplitudes to simulate a comprehensive range of possible vibration scenarios. For example, the effect of low frequencies in combination with high amplitudes versus high

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[2] Model 54601B, Hewlett-Packard, 3000 Hanover Street, Palo Alto, CA 94304

frequencies combined with low amplitudes. Therefore, a total of nine clinically relevant vibration scenarios were tested in vitro.

Ex Vivo Apparatus and Materials

Bench Top Apparatus Design

An experimental apparatus was used to test the effects of vibration on frictional forces as different orthodontic brackets were retracted along an archwire (Fig. 2). The bench-top apparatus consisted of an impulse hammer constructed of 0.036 inch diameter stainless steel wire[3] bonded to a flexible diaphragm serving as the vibration source. Movement of the flexible diaphragm was generated by an electromagnet. A waveform generator[4] was used to input each of the nine frequency and amplitude combinations into the electromagnet. Vibration of the archwire was measured using the same piezoresistive accelerometer as used in vivo to ensure similar frequency and amplitude values to those measured from human subjects.

The impulse hammer was positioned just below the fixed, horizontal 0.017 x 0.025 inch stainless steel wire[5] which was held in place with retention bolts and washers. The retention bolts were attached to a plexiglass plate, which in turn was bolted to a large steel plate atop two cement columns. This secure mounting reduced the effects of extraneous vibrations. In addition, the testing area was maintained at 37 degrees Celsius by a heated fan and measured with a digital thermometer to simulate intraoral temperature.

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[3] DENTSPLY GAC International, 355 Knickerbocker Ave., Bohemia, NY 11716
[4] Model 33120A, Hewlett-Packard, 3000 Hanover Street, Palo Alto, CA 94304
[5] DENTSPLY GAC International, 355 Knickerbocker Ave., Bohemia, NY 11716
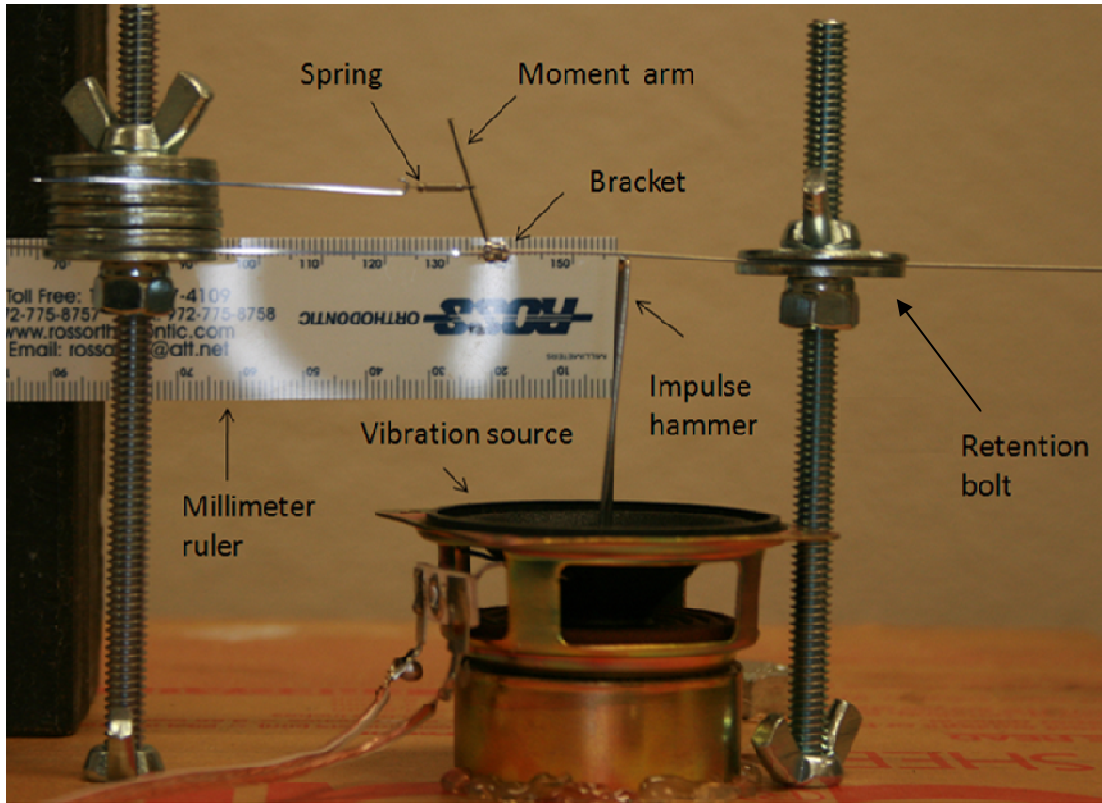
Fig. 2. Experimental apparatus. A 150-cN nickel titanium closed coil spring was attached to a moment arm at a distance 10 mm from the center of the bracket slot. The moment arm, constructed of 0.032 inch diameter stainless steel was notched to allow attachment of the spring and was also bonded to the back of each bracket. Each bracket was ligated to a 0.017 x 0.025 inch stainless steel wire. The wire was held in place via retention bolts on either side. A millimeter ruler was placed directly behind the bracket to gauge movement. The impulse hammer was constructed of 0.036 inch stainless steel wire which was bonded to the vibration source, a speaker wired to a waveform generator (not shown). The waveform generator was used to input a square wave signal to the impulse hammer.

Brackets

Two different types of orthodontic brackets, one with passive ligation and the other active, were compared. Both bracket ligation types were upper right canine brackets with a 0.022 inch inciso-gingival slot dimension. The bracket representing passive ligation was the DamonQ[6] self-ligating bracket (Fig. 3A). The term passive indicates that no component of the bracket actively engages the wire into the slot. DamonQ's ligation apparatus was composed of stainless steel and had a sliding door to retain the archwire (Fig. 3B). These brackets had a 0.022 x 0.028 inch slot dimension and a mesio-distal width of 2.9 mm. The bracket prescription was -9 degrees torque, which would clinically move the root of the tooth labial, and +5 degrees tip, which would tip the root of the tooth distal relative to the crown.

Active ligation denotes that some component of the ligation system, either a bracket door or elastomeric tie is actively engaging the wire into the slot. For this study, a conventionally ligated twin bracket, Unitek Victory Series[7] represented active ligation (Fig. 3C). The Victory Series twin bracket utilized an elastomeric ligature[8] to retain the archwire in the bracket slot (Fig. 3D). The ligature was stretched once to approximately three times its original lumen size to simulate the elastic force decay that occurs in vivo. The conventional bracket was also composed of stainless steel and had a slot size of 0.022 x 0.028 inch and a mesio-distal width of 3.4 mm. The bracket prescription was -7 degrees torque, which would clinically move the root of the tooth labial, and +8 degrees tip, which would tip the root of the tooth distal relative to the crown.

[6] Product #491-6480, ORMCO Corporation, 1717 West Collins, Orange, CA 92867
[7] Product #017-880, 3M Unitek, 2724 South Peck Rd., Monrovia, CA 91016
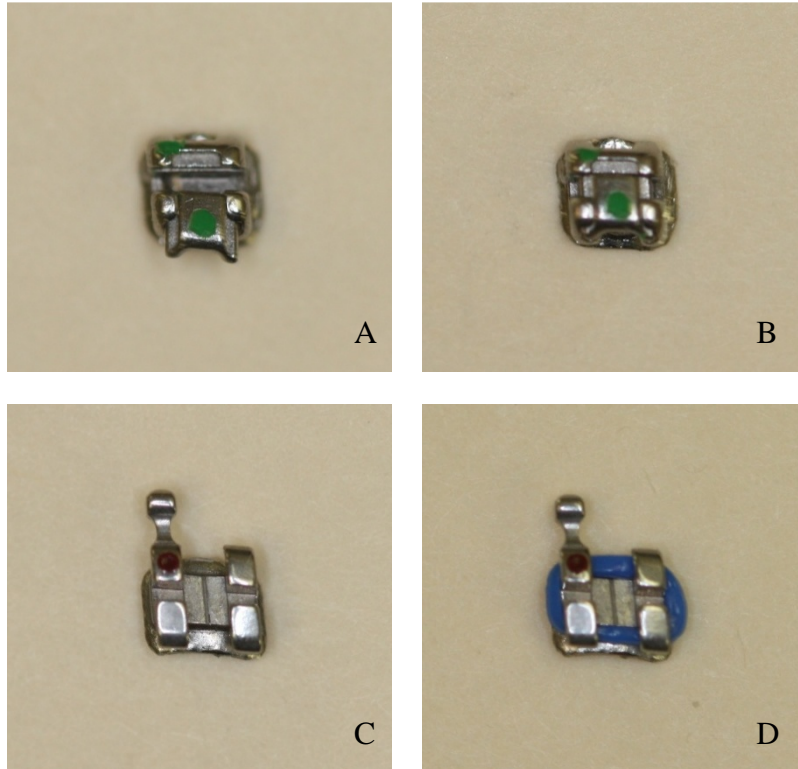[8] 3M Unitek, 2724 South Peck Rd., Monrovia, CA 91016

Fig. 3. Brackets. A. DamonQ (Ormco) 2.9 mm wide, door open
B. DamonQ, door closed C. Unitek Victory Series Twin (3M) 3.4
mm wide D. Victory Series Twin with attached elastic ligature

Nickel Titanium Closed Coil Spring

A nickel titanium closed coil spring[9] was pre-calibrated to test the accuracy of and quantify the unloading force delivered, plus determine the range over which the unloading force was relatively steady. The manufacturer reported force value on the spring used during this study was150-cN. Recent studies have found inconsistency in these reported values over clinically applicable deactivation ranges (Maganzini et al. 2010). It is for this reason that spring calibration was completed at four different time points during this study: time 1, prior to beginning any trials, time 2, after 30 trials were completed, time 3, after 60 trials were completed, and time 4, after all 90 trials were completed. During calibration, the spring was held vertically with one end hooked to a stable bench-top extension arm and the other hooked to a container in which increasing amounts of weight was added. Weight, in grams, was added until a maximum spring extension of approximately 18 mm was reached. At that point, deactivation of the spring was tested by removing 1 to 10 gram increments until spring extension returned to 0 mm. The temperature was maintained at 37 degrees Celsius for all calibrations to simulate intraoral temperature conditions.

Results of the four spring calibrations revealed an average force level of 145.9 cN and a range 128 to 178 cN, between 10 mm and 2 mm of spring extension during deactivation. The average force difference at 10 mm and 2 mm of spring extension over the four calibrations was 35 cN. This amount of force decay is less than 50 cN which has been found to be an acceptable diffference in previous studies (Maganzini et al. 2010). A graph representing the unloading forces over the deactivation range of 10 mm to 2 mm is shown in

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[9] DENTSPLY GAC International, 355 Knickerbocker Ave., Bohemia, NY 11716

Figure 4. It is important to note that the spring maintains similar force levels over all four

calibration points ensuring that accurate force delivery occurred during the entire study (Fig.

4).

<p style="text-align:center">Bracket-Moment Arm Configuration</p>

Each bracket had a 0.032 inch diameter stainless steel wire[10] bonded[11] to its mesh

pad, extending superiorly, perpendicular to the gingival and incisal walls of the bracket slot

and parallel to the pulpal wall of the bracket slot. A mounting jig fixed atop standardized

graph paper was used to ensure the vertically bonded wire was orientated the same for all 90

brackets. The wire was notched 10 mm above the center of the bracket slot to ensure

stabilization of the150-cN nickel titanium closed coil spring (Fig. 5). This configuration

produced a 1500 cN-mm moment between the bracket and archwire, mimicking intraoral

canine retraction when a 150-cN force is applied to the bracket hook located 10 mm from the

tooth's center of resistance.   It was under this clinic scenario that bracket archwire frictional

resistance was measured. The other end of the spring was secured to a hooked archwire held

in place by retention bolts and washers (Fig. 2).

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[10] DENTSPLY GAC International, 355 Knickerbocker Ave., Bohemia, NY 11716
[11] Transbond XT, 3M Unitek, 2724 South Peck Rd., Monrovia, CA 91016
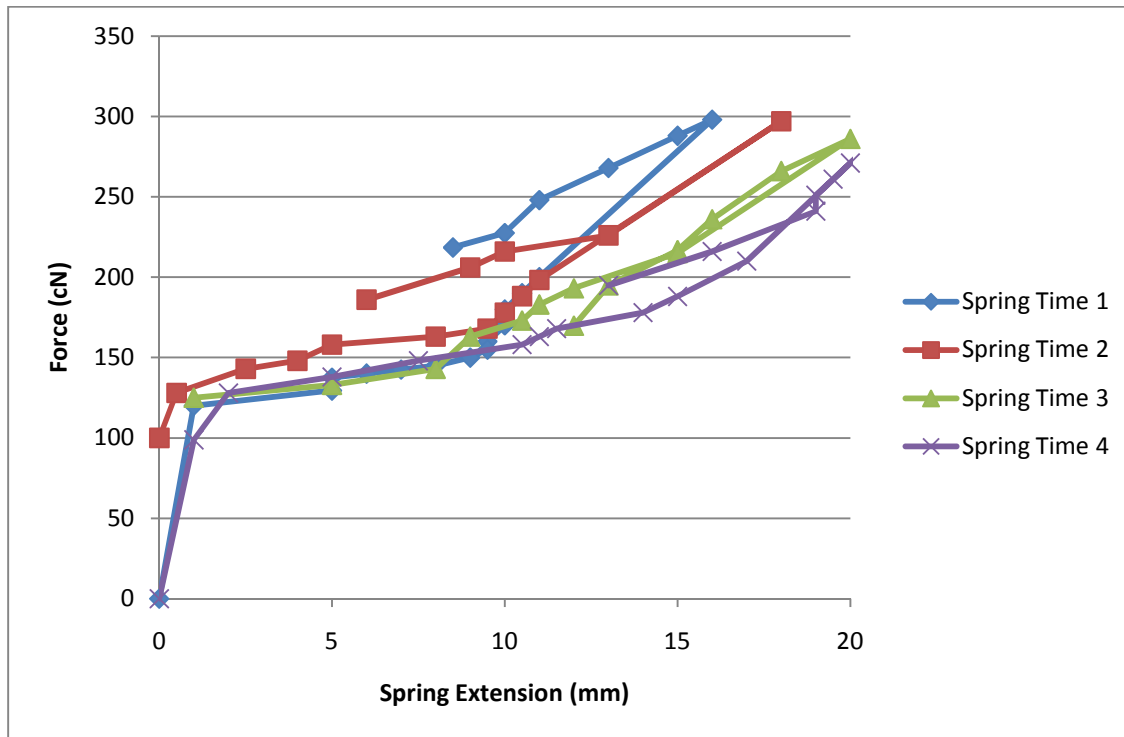
Fig. 4. 150-cN nickel titanium closed coil spring properties. The graph shows the loading and unloading forces (cN) versus spring extension (mm) of a nickel titanium closed coil spring over four trials. The flattest portion of the curve is between 10 mm and 2 mm of unloading or "deactivation." Therefore, force delivery was approximately 150-cN during the defined range of deactivation where spring length changed from 10 mm to 2 mm.
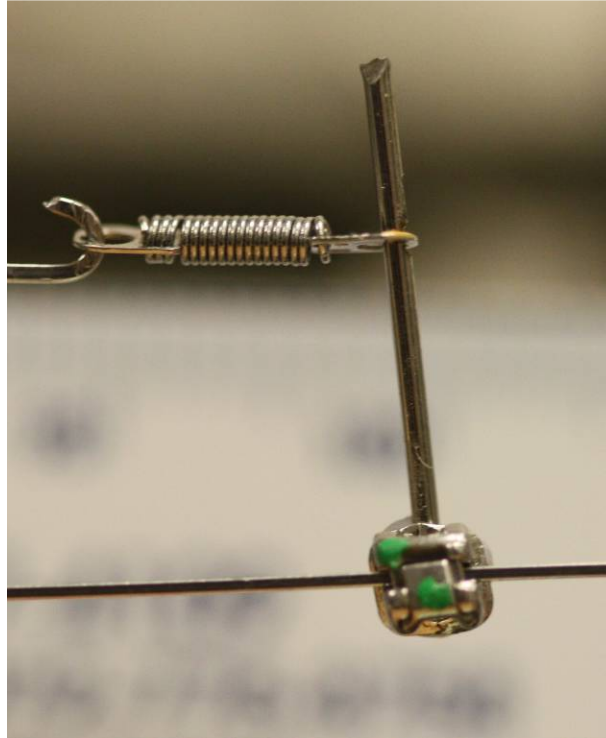
Fig. 5. Bracket-moment arm configuration. A notch was placed10 mm from the bracket slot for retention of the coil spring.

Experimental Research Design

The experimental design was a three-factor non-repeated measures study. Independent variables included: vibration frequency, vibration amplitude, and ligation method. Frequency and amplitude both had 3 levels of measurement derived from clinical values, representing low, medium, and high. More specifically, frequencies of 60, 100, and 140 Hz and amplitudes of 110, 150, and 190 mV were used. Bracket ligation contained two levels, active and passive. The dependent variable, bracket-archwire frictional resistance, was measured as a function of time (seconds) for each bracket to move while subjected to the prescribed tipping moment; hence the bracket-moment arm unit was displaced 10 mm from the passive state and monitored until it reached 2 mm of displacement.

Ex Vivo Measurement of Bracket Dynamic Mechanics

The frictional resistances of the two ligation types, active and passive, were measured at all nine frequency and amplitude combinations. A convenience sample was used, as the chosen brackets were representative of brackets used in the UMKC Graduate Orthodontic Clinic. In addition, it was not possible to test all brackets within the scope of this study. Five brackets per ligation type were used at each frequency-amplitude combination for a total of 90 tests. Randomization of the 90 tests was done using commercial software. A new bracket for each test was used to ensure accurate repeatability of the trials and to account for any individual bracket differences that may have had an effect on friction testing. In addition, a new archwire was used for each trial to control for any scratching created during bracket testing. All results of the duplicate bracket trials were incorporated into the data analysis.

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Each bracket-moment arm unit was individually secured onto the archwire. The DamonQ bracket was attached by closing the sliding door mechanism. While a stretched elastomeric ligature was placed around the Unitek Victory Series bracket tie wings to encompass the wire. Upon attaching the coil spring to the moment arm, the bracket-moment arm-spring complex was pulled along the horizontal archwire until the spring was activated 12 mm. The bracket was then released to come to rest at static equilibrium, the position where friction at the bracket-archwire interface could not be overcome by the force of the 150-cN spring. At this point, the prescribed vibration was introduced into the system. The coil spring had an unloading force of 150-cN over the deactivation range from 10 mm to 2 mm (Fig. 5). Therefore, time, in seconds, for each bracket to be retracted along the archwire from 10 mm to 2 mm of spring extension was recorded (Fig. 6).

In order to accurately measure bracket movement, a millimeter ruler was mounted adjacent to the bracket-moment arm. In addition, a video camera was used to record each trial so bracket movement could be analyzed using commercial software. For each bracket, frequency, and amplitude combination, video images were viewed frame by frame to determine time-dependent changes in bracket position. Measurement bias was controlled by having three trained examiners view the video images and record bracket movement for each trial. All values from the three examiners were recorded and averaged to determine the time value for each trial. Further, brackets that did not move the entire distance from 10 mm to 2 mm were assigned a maximum time value of 900 seconds. This maximum time of 900 seconds was determined by the examiners as an acceptable time limit due to time limitations

associated with the study. Two weeks later, random trials were viewed to ensure

reproducibility of the bracket movement measurements.
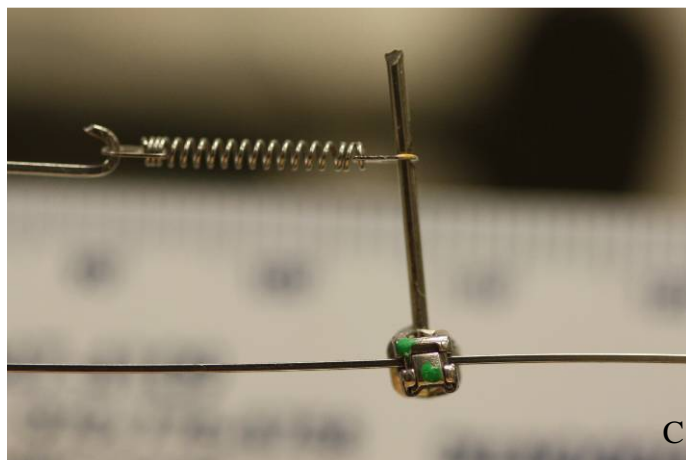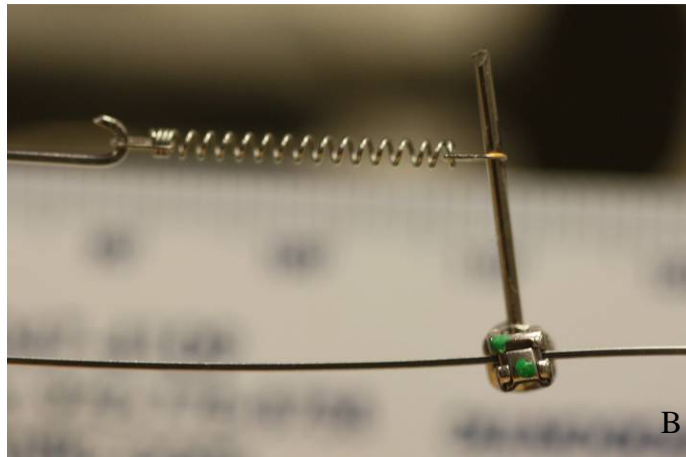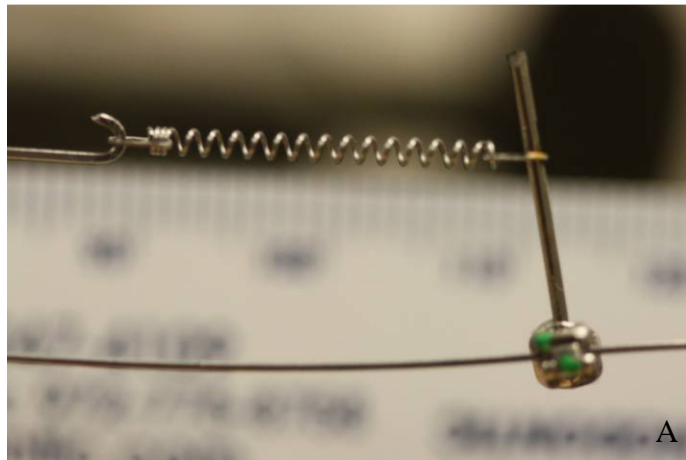
Fig. 6. Spring extension. A. 12 mm B. 10 mm C. 5 mm

Data and Statistical Analyses

Statistical Analyses

A backward linear regression was used to determine which, if any, independent variables did not have a significant effect on the dependent variable, bracket-archwire frictional resistance. The F-test via a two-factor ANOVA[12] ($\alpha = 0.05$) was then used to test for main effects, as well as, interaction effects of the remaining independent variables. If the omnibus test indicated significant differences in friction for the differing independent variables, the Ryan-Einot-Gabriel-Welsch F Post Hoc analysis was used to assess pair wise comparisons and allow for control of type I error rate.

Predictive Modeling

Since time and resource limitations allowed for only 90 total tests to be completed, arbitrary missing values were dealt with using Markov chain Monte Carlo (MCMC) full-data imputation[13]. This technique was used to create 5000 samples. Averages from these samples were used to fill missing values. Response Surface Regression (RSREG) was then used to predict the variance seen in the original model for a larger sample set. Upon running the RSREG, the square root of time (seconds) was used to create a normal dataset. Further, the data were tested to make sure the model fit. Canonical analysis showed regions of optimum response of the independent variables, mV and Hz, for both active and passive brackets. These results were then used to create a response surface contour and 3-D plot of predicted time values over a range of frequencies and amplitudes for each ligation, as well as, compared response differences between the two ligation methods.

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[12] SPSS Version 18.0, 223 S. Wacker Dr., Chicago, IL 60606
[13] Statistical Analysis System, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513

CHAPTER 3

RESULTS

Clinical Vibration Values

There was a considerable range of archwire vibration values found during clinical

measurements. Frequency values ranged from 45.3 to 208 Hz. While amplitude values

ranged from 84.4 to 240 mV. Average values from both vibration measurement sessions,

Time 1 (T_1) and Time 2 (T_2), for each subject are presented in Table 1, as well as, overall

averages for all subjects combined. The overall averages and standard deviations were used

to determine ex vivo vibration values.

Intraclass Correlation Coefficients (ICC) were calculated for frequency and amplitude

to evaluate subject variability at both time points. At T_1, the ICC for frequency was 0.26

while at T_2 the value was 0.63. Amplitudes showed a similar trend with an ICC of 0.28 at T_1

and 0.52 at T_2.

TABLE 1

CLINICALLY MEASURED MEAN AMPLITUDES AND FREQUENCIES
DURING INCISION

Subject	Mean Amplitude (mV)	SD	Mean Frequency (Hz)	SD
1	191.3	± 52.04	129.88	± 36.26
2	121.88	± 28.07	96.49	± 28.34
3	154.38	± 18.17	101.22	± 23.46
4	157.53	± 13.34	82.72	± 28.62
5	130.85	± 14.22	79.95	± 17.95
6	152.05	± 49.60	99.48	± 47.49
Overall	151.33	± 39.22	98.29	± 41.19

Frictional Resistance Measurements

The results from all 90 bracket trials were included in the data analysis. Of the 90 total trials, 33 bracket-moment arm units did not slide when the prescribed vibration was applied. These trials were assigned a maximum time value of 900 seconds, as discussed prior. Of the 33 trials that did not slide, 17 were passive ligation and 16 were active ligation. For the given frequency levels, the distribution of non-sliding trials was 12 low frequency, 10 medium frequency, and 11 high frequency trials. For the given amplitude levels, the distribution of non-sliding trials was 15 low amplitude, 8 medium amplitude, and 10 high amplitude trials. Due to the number of outliers, time values were converted to natural log time to normalize the data and analyze significant effects.

Analysis using a backward linear regression indicated the independent variable, frequency of vibration, had no significant effect on the dependent variable, bracket-archwire frictional resistance (p=0.317). Variation in frequency accounted for only 1.1% of the variation in frictional resistance. Since variation in frequency of vibration had the smallest influence on variation in the dependent variable, only the two remaining independent variables were used during further analysis.

A 2-way ANOVA was used to analyze the effects of amplitude of vibration and ligation method. Results showed no statistically significant effect of ligation method on frictional resistance (p = 0.100). However, there was a statistically significant difference in frictional resistance as a function of amplitude (p = 0.041). Means and standard deviations of frictional resistance (ln, seconds) as a function of bracket ligation method and amplitude can be found in Table 2.

The partial η^2 for ligation method and amplitude were 0.032 and 0.073, respectively. These values indicate the percent of variability in frictional resistance explained by each independent variable. Therefore, in this study, 3.2 % of variation in bracket-archwire frictional resistance could be explained by ligation method, while 7.3% of variation was explained by amplitude.

The post-hoc analysis indicated significant differences amongst amplitude levels at the $\alpha = 0.05$ level. Frictional resistance was significantly greater in the low amplitude group as compared to the medium and high groups, which were similar to each other. Average natural log (ln) time values for amplitude, regardless of ligation method, can be found in Table 3.

TABLE 2

FRICTIONAL RESISTANCE AS A FUNCTION OF BRACKET LIGATION AND
AMPLITUDE: MEAN AND STANDARD DEVIATION (SD) VALUES

Bracket Ligation*	Amplitude[+]	Mean**	SD	N
Passive	110 mV	5.64	$\pm$ 1.71	15
	150 mV	4.47	$\pm$ 2.61	15
	190 mV	4.21	$\pm$ 2.45	15
Active	110 mV	5.97	$\pm$ 1.02	15
	150 mV	5.14	$\pm$ 1.38	15
	190 mV	5.14	$\pm$ 1.34	15

* No significant difference in frictional resistance as function of ligation method (p = 0.100)
[+] Significant difference in frictional resistance as function of amplitude level (p = 0.041)
$\alpha = 0.05$
**Values represented as natural log time (seconds)

TABLE 3

FRICTIONAL RESISTANCE AS A FUNCTION OF AMPLITUDE:
MEAN AND STANDARD DEVIATION (SD) VALUES

Amplitude (mV)	Mean[+]	SD	N
110[a]	5.80	$\pm$ 1.39	30
150[b]	4.81	$\pm$ 2.08	30
190[b]	4.67	$\pm$ 2.00	30

[a,b]Statistically significantly different at the $\alpha = 0.05$ level
[+]Values represented as natural log time (seconds)

Predictive Modeling

The response surface regression was computed using the square root of time (sqrt time). This conversion was done to normalize the data. The overall regression relationship, utilizing the independent variables, amplitude and frequency, for the dependent variable, sqrt time, was significant for both the passive ($p = 0.005$) and active ($p = 0.008$) ligation bracket types.

Upon testing the effects of the independent variables, results for the passive bracket type indicate that amplitude ($p = 0.02$) and frequency ($p = 0.04$) both significantly contribute to the response surface model. The active bracket type had similar values for amplitude ($p = 0.03$) and frequency ($p = 0.04$). Results of the canonical analysis and ridge analysis can be found in Table 4. These values describe the shape of the predicted response surface, and the regions of optimum response representing the vibration scenario with the highest amount of friction for each bracket type. 3-D plots of predicted frequency and amplitude effects can be found in Figures 7 and 8, respectively. The 3-D plot of sqrt time versus amplitude and frequency for both active and passive ligation bracket types can be found in Figure 9.

The predictive modeling plots showed very different patterns between bracket types. In addition, estimated time values at low and high frequencies demonstrate different trends compared to low and high amplitude values. Looking at frequency effects, predicted time values were lowest within the given frequency range at a frequency of 60 Hz. This low friction scenario occurred with the passive ligation brackets at a sqrt time value of 1 second. At the same frequency, active ligation had a 7-fold greater time value. At a frequency level of 100 Hz, active ligation brackets had 2 times greater friction than passive ligation brackets,

with time values of 9.5 sqrt seconds for active and 5 sqrt seconds for passive ligation brackets. At a frequency of 145 Hz, active and passive ligation brackets are predicted to have similar amounts of frictional resistance with a sqrt time value of 7 seconds for both bracket types.

Amplitude plots showed a more similar pattern between bracket types than the predicted frequency curves. At low amplitudes of approximately 95 mV, the two bracket types were predicted to experience the same amount of frictional resistance. Both active and passive plots had a predicted sqrt time value of 9 seconds at 95 mV. At 150 mV, the sqrt time for passive ligation brackets was 7 sqrt seconds while active ligation brackets reached 10 sqrt seconds. As amplitude values increased, frictional resistance decreased for both bracket types. Within the given amplitude range, both passive and active ligation brackets reached the lowest predicted sqrt time at amplitude levels just over 200 mV, although passive ligation brackets consistently experienced greater reduction in friction with a sqrt time value of 1 second, which was 5 times lower than for its active counterpart.

The vibration scenario with the lowest predicted frictional resistance under the given predicted range was the passive ligation at frequency and amplitudes levels of 58 Hz and 202 mV. The estimated sqrt time value at this vibration scenario was just under 1 second. Active ligation brackets were predicted to experience the least amount of friction within the given predicted range at 150 Hz and 205 mV with an estimated sqrt time value of 5 seconds.

TABLE 4

RESPONSE SURFACE REGRESSION ANALYSIS

Bracket Ligation	Independent Variables	Critical Values*	Eigen Values
Passive	Amplitude (mV)	111.28	-1.00
	Frequency (Hz)	121.61	-2.99
Active	Amplitude (mV)	99.72	-1.51
	Frequency (Hz)	120.42	-2.27

*Critical values represent vibration scenarios with the greatest predicted frictional resistance

Fig. 7. Predicted 3-D frequency plot.   Frictional resistance (SQRT Time) is shown over a range of frequencies (Hz) for passive (brown) and active (green) brackets
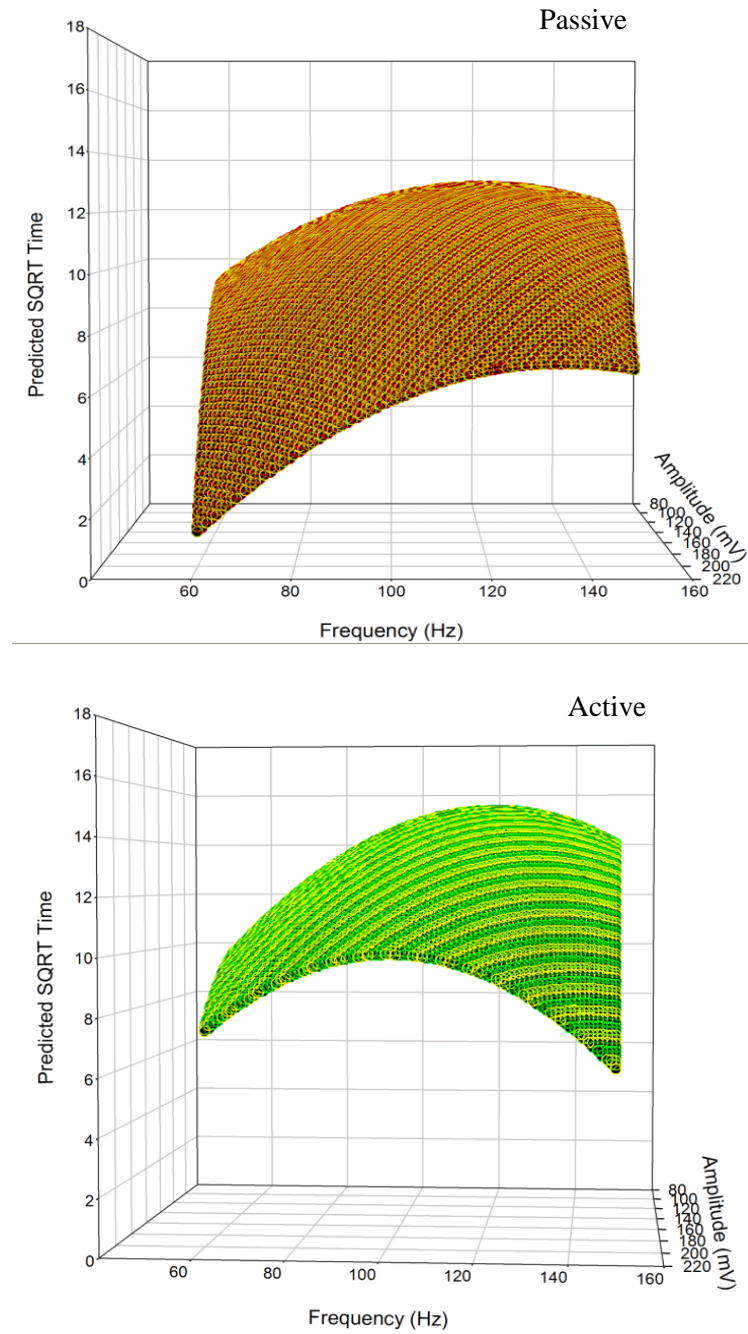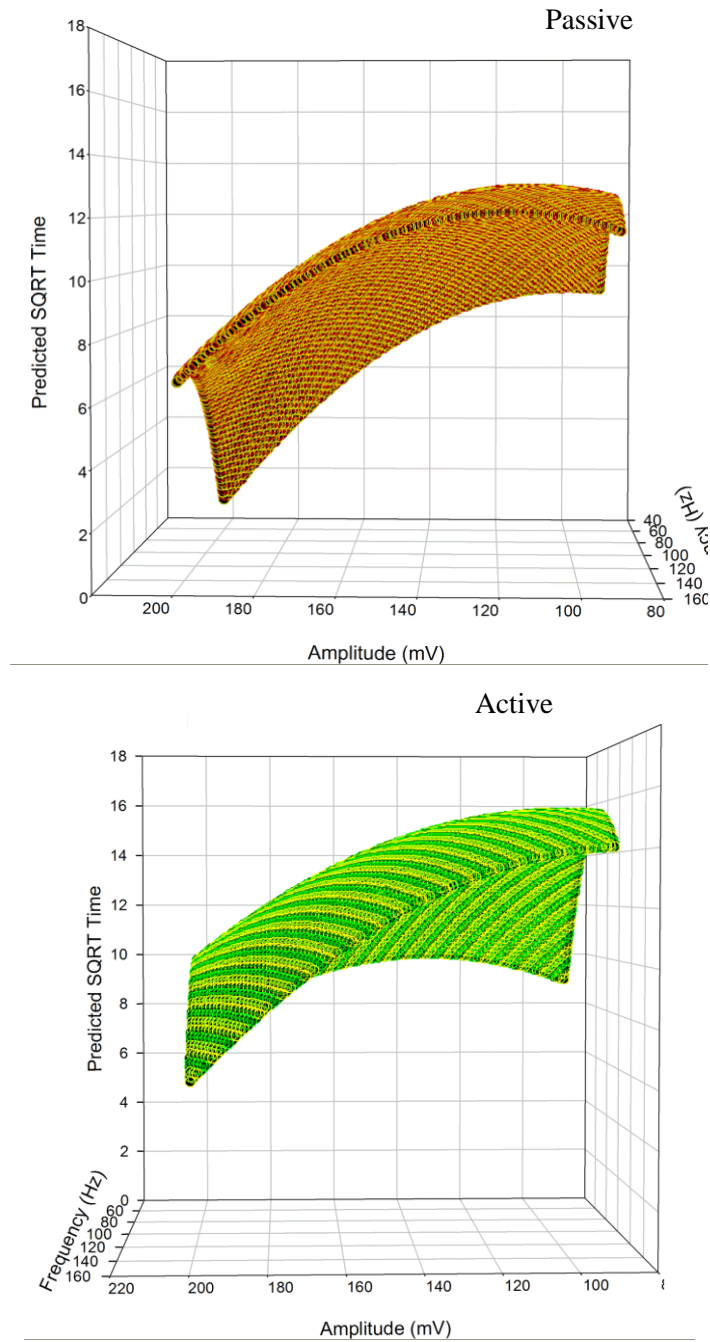
Fig. 8. Predicted 3-D amplitude plot. Frictional resistance (SQRT Time) is shown over a range of amplitudes (mV) for passive (brown) and active (green) brackets

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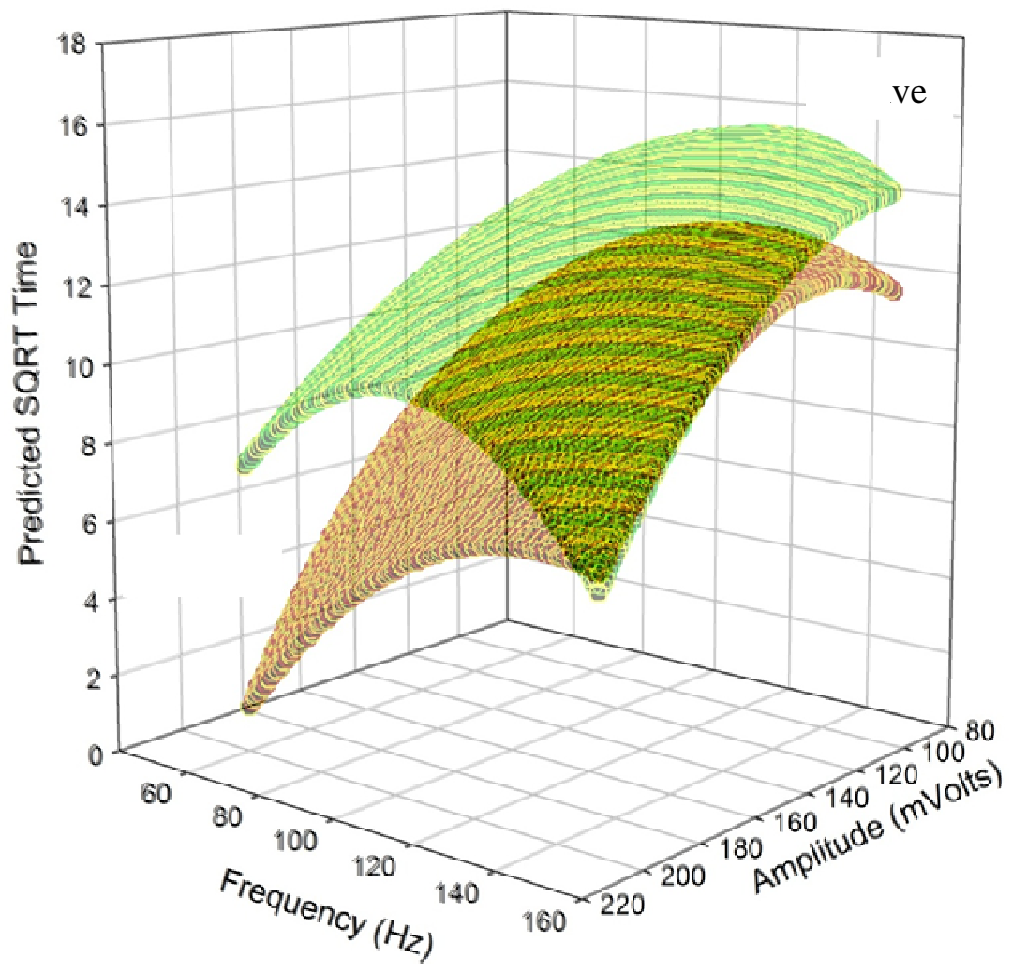
Fig. 9. Predicted 3-D frequency and amplitude plot. Frictional resistance (SQRT Time) is shown over a range of frequencies (Hz) and amplitudes (mV) for passive (brown) and active (green) brackets

CHAPTER 4

DISCUSSION

Archwire Vibration Measurements In Vivo

Many journal articles have alluded to the idea that archwire perturbations occurring during mastication influence the nature of the bracket-archwire interface during orthodontic tooth movement. There are no known studies that have measured this phenomenon clinically. Therefore, the first part of this study measured in vivo perturbations at the bracket-archwire interface associated with human mastication. Although, previous studies have investigated tooth mobility during orthodontic tooth retraction under various occlusal loads (Tanaka et al. 2005), movement at the level of the appliance itself was measured with the current study.

The in vivo investigation was pilot in nature, but revealed some interesting findings to apply towards future studies. When combining all subject bite sessions, correlation values improved from T_1 to T_2, indicating less subject variability in bite recordings at T_2 compared to T_1. This would suggest a possible learning curve, i.e. subjects' values normalized with increased bite trials. Training sessions should be utilized in the future. Possible sources of variability in vibration recordings could stem from operator ligation of the accelerometer to the canine bracket, consistency of food substance, and biting techniques of subjects. Further in vivo studies investigating the influence of mastication on orthodontic archwire perturbations are necessary.

Ex Vivo Friction Measurements

Time dependent changes in bracket position were used to represent the energy necessary to ameliorate the friction for each bracket-archwire combination. These values were then used as an indicator of the most efficient bracket ligation and archwire vibration to be used during the sliding of a canine along an archwire clinically. Other friction studies have used units of force (N), sometimes presented inappropriately as units of mass (kg), and percentages of friction reduction to quantify bracket-archwire sliding resistance (Drescher et al. 1989; Articolo and Kusy 1999; Braun et al. 1999; Gandini et al. 2008). The results of the current ex vivo study revealed that brackets subjected to medium and high amplitudes of archwire vibration experienced a greater reduction in frictional resistance as compared to those under low amplitude conditions. Thus, supporting the research hypothesis, variation in amplitude of archwire vibration has a differential effect on bracket-archwire frictional resistance.

Further, the results demonstrated that bracket ligation method and variation in frequency of archwire vibration had no statistically significant effect on bracket-archwire frictional resistance. This fails to support the research hypothesis, and therefore, there is no differential effect of frequency of archwire vibration or ligation method on bracket-archwire frictional resistance. This disagrees with a previous investigation which found significant differences in frictional forces between passive and active brackets similar to the two types tested in the current study (Cacciafesta et al. 2003). In this previous study, frictional forces for the passive ligation were nearly 66% lower for static friction and 60% lower for kinetic friction as compared to the active ligation (Cacciafesta et al. 2003). Although the brackets

were retracted along an archwire similar to the current experiment, Cacciafesta and collegues (2003) did not utilize vibrations or clinically relevant tipping moments and therefore bracket width and binding were not an issue. This is most likely the reason for frictional differences between the current and previous studies.

It is evident that there was an amplitude threshold that influenced the stick-slip behavior of the bracket and archwire, in turn, reducing frictional resistance. Medium and high amplitude values of 150 mV and 190 mV applied to the archwire decreased frictional resistance nearly 20% more than low amplitude trials of 110 mV. As mentioned prior, these differences in friction reduction did not occur with variation in frequency of archwire vibrations. This indicates that the stick-slip behavior of the bracket-archwire interface is more affected by vibration amplitude, or amount of vertical displacement of the archwire, rather than vibration frequency which is how fast the wire is moving up and down. A comparable study by O'Reilly and collegues (1999), applied vibrations using a fixed frequency of 81 cycles per minute while varying the amplitude of wire displacement, 0 mm, 0.25 mm, 0.5 mm, and 1 mm. A decrease in resistance to sliding of 10% for 0.25 mm, 47% for 0.5 mm, and 80% for 1 mm of vertical wire displacement occurred (O'Reilly et al. 1999). Perhaps in the current study a larger percent reduction in sliding resistance would have occurred if a greater range of amplitude values were examined, for example, testing the effects of values 2 standard deviations away from the mean.

The applied archwire vibrations were unable to overcome the normal forces created between the bracket and archwire in 33 of the 90 lab trials. Therefore, a maximum time value was assigned to these trials. The distribution of trials that did not move amongst frequency

levels was nearly equal for all three levels, low, medium, and high, although amplitude levels did have variation in distribution of non-sliding trials over the three levels. Low amplitudes of 110 mV had 15 of the 33 non-sliding trials, or 45%, while medium amplitudes of 150 mV had 8 non-sliding trials, and high amplitudes of 190 mV had 10 non-sliding trials. Therefore, low amplitude vibrations were not as effective as medium or high amplitudes in reducing friction at the bracket-archwire interface to allow bracket movement. Both bracket types equally contributed to the trials that had no movement; passive ligation had 17 trials and active ligation 16. This would indicate that for both bracket types either the normal force created during bracket tipping or the normal force from ligation was too great to be overcome by the 150-cN retraction force or the vibrational energy input, or both.

Previous studies have found that increasing the bracket-archwire contact angle has a significant effect on resistance to wire sliding (Articolo and Kusy 1999). For example, in one study, as bracket angulations went from $\theta = 0°$ to $\theta = 11°$, there was a 76-fold increase in archwire sliding resistance (Articolo and Kusy 1999). The current study utilized a clinically applicable tipping moment of 1500 cN-mm, but did not measure the contact angle created. Rather the normal force at the edge of the bracket slot and archwire could be calculated based on the value of the moment and bracket width. The resulting normal forces due to bracket tipping were 517 cN for passive ligation and 441 cN for active ligation. The 76 cN difference between the two bracket types was due to the passive bracket having a mesial distal width of 2.9 mm while the active bracket was 3.4 mm. One study reported a significant increase in friction when comparing a bracket 2.2 mm in width to those 3.3 mm and 4.2 mm in width (Drescher et al. 1989). The narrowest bracket had 25% more friction

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compared to the greater widths which performed the same (Drescher et al. 1989). This

supports the notion that the effect of binding may influence bracket sliding just as much, if

not more, than the normal forces created by ligation. In addition, a 17 x 25 inch stainless

steel wire was used during current testing, which clinically, would allow for easier sliding

mechanics than larger wires, but at the cost of allowing greater dental tipping. This

phenomenon was evident in the 33 trials in which bracket-archwire binding was too

significant for vibrations and retraction force to overcome.

Several studies have evaluated bracket-archwire frictional resistance between active

and passive ligation in the absence of simulated clinical scenarios of canine retraction. These

studies would give the best indication of frictional effects solely due to the normal forces of

ligation. There are conflicting conclusions when evaluating steady state friction studies. As

mentioned prior, one study found significantly less friction with passive ligation under

conditions with 3 different wire materials and 3 different wire sizes (Cacciafesta et al. 2003).

Another study found significant differences between passive and active ligation bracket types

only under conditions with small nickel titanium archwires (Tecco et al. 2007). When full

sized stainless steel archwires were tested, no significant differences in friction were

measured between active and passive ligation methods (Tecco et al. 2007). A major

limitation of these studies was that they were completed under ideal conditions, in a passive

configuration which negates misalignment of teeth during the leveling phase or tipping

moments as forces are applied to teeth clinically.

It is notable that the effect of vibration applications on the stick-slip behavior between

two surfaces is important to several fields of study other than orthodontics. Much can be

learned from similar experiments done at the nano-, micro-, and macroscopic level. Similar to what was found during the current macroscopic investigation between two materials, an orthodontic bracket and archwire, one study utilizing molecular dynamics found a reduction of friction and stick-slip behavior between two surfaces by mechanical excitations utilizing low energy oscillations of frequency and amplitude (Urbakh et al. 2004). The model demonstrated a complete elimination of stick-slip during periods of oscillations as compared to those without. These momentary decreases in surface contacts provided an immediate release of the normal force of binding similar to what occurred during this study as the brackets overcame archwire binding in 57 of the 90 trials.

Predictive Modeling

The results of the predictive modeling analysis gave an indication as to what trends may have occurred with a greater number of tests performed. Since, optimum reduction in bracket-archwire frictional resistance is the goal during canine retraction, it is therefore important to analyze the predicted scenario within the plotted frequency and amplitude range with the least amount of friction for each ligation type. For passive ligation, frequency and amplitude levels of 58 Hz and 202 mV are predicted to produce the lowest amount of bracket-archwire friction, while active ligation is predicted to experience the least amount of friction at 150 Hz and 205 mV. It is important to note that due to the nonlinear shape of the frequency plot for active ligation, a significant reduction in frictional resistance also occurs at a frequency of 55 Hz and amplitude of 200 mV, although the frictional resistance is still predicted to be 6 times greater than that of passive ligation at the same vibration level.

There is a more similar trend between the two bracket types with the amplitude plot, in which both bracket types demonstrate low amplitudes having high friction and high amplitudes having low friction. Since both bracket types are shown to perform best at extreme amplitudes greater than 200 mV, this would agree with other studies that demonstrated the greatest friction reduction at levels with the largest vertical wire displacement (O'Reilly et al. 1999). It would be interesting to examine in further investigations if archwire vibration amplitudes around 200 mV or greater can be consistently reproduced clinically, and if so, with what food substrate or mastication force. Future studies are needed to determine which in vivo mastication conditions provide the desired amplitude and frequency levels to produce optimal bracket-archwire friction reduction.

Limitations of Study

The major limitation of the current study is that testing was completed ex vivo not in vivo. Although in vivo measurements were used to gauge the magnitude of frequency and amplitude of vibrations used during bracket friction testing, the efficiency of tooth movement can only truly be evaluated in the environment in which brackets and archwires are normally used, the oral cavity. As with any ex vivo study, there are limitations when translating the results from this investigation to in vivo application. For example, ex vivo testing could not account for all intraoral factors, such as saliva, food and beverages, and temperature fluctuations, which may influence nickel titanium spring properties, elastomeric ties, as well as, the bracket-archwire interface. Further, the simulated canine retraction in this study did not account for the periodontal resistance and remodeling that occurs during physiologic tooth movement. An advantage of conducting ex vivo research investigations is the ability to

control for confounding variables of the intraoral environment that may differ from subject to subject and over time within the same subject. Researchers must strive to use ex vivo methods of testing that are standardized from study to study in order to compare the conclusions from different studies on similar testing scenarios. Since very few studies have been conducted on orthodontic archwire vibration, there was no standardization to base the current study. This created a limitation when attempting to compare the results of this study with others.

Future Studies

Future studies should include more in vivo investigations of the effect of archwire perturbations and consequent influences on the stick-slip behavior of the bracket-archwire interface. While significant reductions in frictional resistance occurred with medium and high amplitudes of vibration during ex vivo testing, one must investigate if these vibrations influence in vivo canine retraction in a similar way. It would be interesting to compare the stick-slip behavior of a multitude of orthodontic brackets that were not able to be tested within the scope of the current study. Future studies should also evaluate the topographic characteristics of the archwire surface. This would indicate if mechanical notching of the archwire corresponds with amount of bracket movement.

Results of the predictive modeling plots give an indication as to which vibration scenarios may be most influential on frictional resistance of the two bracket types. In future studies, it would be interesting to measure intraoral orthodontic archwire vibration on a greater number of subjects than the six used during this study. This would help determine if the clinically measured archwire vibrations on a larger population fall within the predictive

plots, as well as, what food substances or chewing scenarios create the given levels of

archwire vibration.

CHAPTER 5

CONCLUSIONS

1. There were significant differences in bracket-archwire frictional resistance with variation in amplitude of archwire vibration. Medium (150 mV) and high (190 mV) amplitudes significantly reduced friction compared to low amplitude values (110 mV).

2. There were no significant differences in bracket-archwire frictional resistance with variation in frequency of archwire vibration.

3. There were no significant differences in bracket-archwire frictional resistance between passive and active ligation methods.

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APPENDIX A

IRB APPROVAL

CONSENT FORM FOR PARTICIPATION IN A RESEARCH STUDY
Collection and storage of human biomaterials for research

A Pilot Study to Estimate Vibration Associated with Human Mastication during Orthodontic Treatment

Introduction
You are being asked to volunteer for a research study.

This study is being conducted at the University of Missouri - Kansas City (UMKC), School of Dentistry. The Investigators in charge of this study are Dr. Jeffrey Nickel, Dr. Laura Iwasaki, and Dr. Julie Olson.

You are eligible to participate in this study because you are having orthodontic treatment at the UMKC School of Dentistry Graduate Orthodontic Clinic and you have permanent teeth.

The information in this form is meant to help you decide whether or not to take part. If you have any questions, please ask.

You may take home an unsigned copy of this consent form to think about or to discuss your participation with family or friends before making your decision. You must read and sign the consent form before you have any procedures done for the study. If you decide to participate, a copy of this form will be given to you for your records.

Background
The amount of vibration (small movements) caused when people with braces on their teeth chew their food is unknown. Vibrations during chewing may help teeth to move during orthodontic (braces) treatment. To measure vibrations during chewing a small device called an "accelerometer" will be used. This device helps to measure the speed, the number of movements and the time.

Purpose of This Research Study
The purpose of this research study is to measure the vibrations from chewing during orthodontic treatment. These measurements will be used in future bench-top studies to compare different types of braces.

There will be approximately 6-10 subjects in the study at UMKC School of Dentistry.

Study Procedures and Treatments
If you agree to be in this study, you will be seated in a dental chair and your braces will be checked to be sure that no parts are loose or broken. If your braces are all in place, your upper right "eye-tooth" (canine) will be fitted with a sterilized (clean) accelerometer. This accelerometer will be tied to your braces. For this, a regular wire orthodontic tie (thin metal string) will be used. You will then be asked to bite in a normal way on a small carrot stick using your upper right eye-tooth. You will be given a second carrot stick and asked to bite again in the same way. Each time you bite, the vibrations (small movements) will be recorded and measured.

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In total, you will be asked to bite 5 times. After this, the accelerometer will be removed and your braces checked. You will be asked if you would like to brush and/or floss your teeth.

For this study, you will make 2 visits, about 0.5 hour long each. The study procedures are the same for all subjects in this study. These procedures will take place in the Graduate Orthodontic Clinic at the UMKC School of Dentistry. There are no treatments involved in this study, so the study procedures will not be offered after you have finished the study.

Possible Risks or Side Effects of Taking Part in this Study
Possible risks and discomforts you could experience during this study include:
   Accidental loosening of your braces: It is possible that during the attachment or removal of the accelerometer or during one of the bites on a carrot stick, your braces may come loose. The pressures involved in putting on or taking off the accelerometer are the same as the pressures used in adjusting your braces. The type of bite you will be asked to do is the same as you use while eating normal foods. That is, the chances of one of your braces coming loose are about the same as during your braces treatment and during ordinary eating. If a bracket or band comes loose it will be reattached by one of the study doctors.

   Discomfort due to biting: It is possible that your teeth may be sensitive to the pressure during biting on a carrot stick. You will be asked whether or not your teeth are currently sensitive during eating or biting on food. If your teeth are sensitive the study procedures will be postponed until your teeth are not sensitive.

   Accidental swallowing or aspiration (going down the wind-pipe) of the accelerometer: It is possible that during the study the accelerometer could come loose and accidentally go down your throat. The accelerometer is slightly larger than most pieces of hard candy, so it would be quite difficult to swallow on purpose. In order to try to prevent the accelerometer from going down your throat, you will be seated upright while the accelerometer is being used. In addition, sterile dental floss will be tied to the accelerometer to provide an additional "handle."

It is possible that other rare side effects could occur that are not described in this consent form. It is also possible that you could have a side effect that has not occurred before.

Important Information for Women
Women who are breast-feeding and women who are pregnant can have braces and may participate in this study. There are no known risks of the study procedures to the unborn embryo or fetus or the infant who is breast-feeding.

Possible Benefits of Taking Part in this Study
There are no direct benefits to you for participating in this study

Costs for Taking Part in this Study
There are no additional costs to you to be in this research study. You will be responsible for doctor and or dental clinic charges as usual except for those directly related to the research study. You or your insurance company will have to pay for orthodontic treatment.

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Payment for Taking Part in this Study
To compensate you for yout time and transportation expenses, you will be paid $30.00 per visit to a maximum of $60.00. You will only be paid for the visits you complete.

Alternatives to Study Participation
The alternative is to not participate.

Confidentiality and Access to your Records
Results of this research may be published for scientific purposes or presented to scientific groups; however, you will not be identified. The Institutional Review Board or other regulatory agencies may be given access to research study records and any pertinent medical and dental records which contain your identity. Medical and dental records that identify you and the consent form signed by you will be reviewed to verify the study procedures that were performed and the data (information) reported about you. Medical and dental records from treatment you received prior to giving your consent to participate in this clinical study will also be reviewed, if available, to verify your medical and dental histories and your eligibility for this study. Your medical and dental records will be kept as confidential as possible under local, state and federal law, but absolute confidentiality cannot be guaranteed.

If you should withdraw or be withdrawn from the study, the study data collected prior to withdrawal may still be processed along with other data collected as part of the study. For purposes of follow-up studies and if any unforeseen circumstances arise, subject identification will be filed at UMKC School of Dentistry under adequate security and with accessibility restricted to research personnel only.

By signing this consent form you are authorizing such access to your medical and dental records.

In Case of Injury
The University of Missouri-Kansas City appreciates the participation of people who help it carry out its function of developing knowledge through research. Although it is not the University's policy to compensate or provide medical treatment for persons who participate in studies, if you think you have been injured as a result of participating in this study, please call the investigator, Dr. Jeffrey Nickel, at 816-235-2134 or the IRB Administrator of UMKC's Adult Health Sciences Institutional Review Board at 816-235-6150.

Contacts for Questions about the Study
If you have any questions or concerns regarding this study, or if any problems arise, you may call the study investigator Dr. Jeffrey Nickel, at (816-235-2134). To express concerns of pressure about your participation in the study or ask questions you may also contact the IRB Administrator of UMKC's Adult Health Sciences Institutional Review Board at 816-235-6150.

Emergency Contact
In the event of an emergency, where you feel that it is necessary that you contact an investigator immediately, rather than waiting until regular office hours, you should call Dr. Jeff Nickel at 816-527-0106.

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Voluntary Participation:
Your participation in this research is voluntary; you are free to discontinue participation in this study at any time and for any reason; refusal to participate will involve no penalty or loss of care to which you are normally entitled; you may also discontinue participation at any time without penalty or loss of benefits to which you are entitled. You will be removed from the study, if at any time, it is necessary because of medical reasons. Additionally, you will be informed of any significant findings developed during the course of this research. You volunteer and consent to participate in this research study.

You have read this Consent for Research or it has been read to you. Further, the purpose of the study, risks involved, and procedures which will be performed have been explained to you. You have had the chance to ask questions, and you may ask questions at any time during the course of the study by calling Dr. Jeffrey Nickel at 816-235-2134.

_____   _____
Signature (Volunteer Subject)   Date

_____   _____
Signature (Authorized Consenting Party)   Date

_____   _____
Signature of person obtaining consent   Date

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VITA

NAME

Julie Elizabeth Olson

DATE AND PLACE OF BIRTH

October 11, 1983, Omaha, NE

MARITAL STATUS

Married to David Scott Olson

EDUCATION

5/2001	Diploma	Millard North High School Omaha, NE
5/2005	BA Biology	University of Kansas Lawrence, KS
5/2009	DDS	University of Nebraska Medical Center College of Dentistry Lincoln, NE
8/2011	MS Oral Biology	University of Missouri–Kansas City School of Dentistry Kansas City, Missouri

INTERNSHIP AND/OR RESIDENCIES

7/2009- 8/2011	Orthodontic Residency	University of Missouri–Kansas City School of Dentistry Kansas City, Missouri

PROFESSIONAL ORGANIZATIONS

Omicron Kappa Upsilon
American Association of Orthodontists
American Association of Orthodontists Foundation
American Dental Association
American Student Dental Association
American Association of Dental Research

HONORS

Phi Kappa Phi Honor Society (2003 – current)
American Association of Oral Biologists Award (2009)
Chi-Cheung Chan Orthodontic Award (2009)
Nebraska Board of Regents Scholarship (2005 – 2009)
UNMC Dean's Honor List and Honors Convocation (2005 - 2008)
First Place, Nebraska Dental Association Annual Meeting table clinic presentation (2008)
Third Place, UNMC Student Scientific Professionals' Day table clinic presentation (2008)
Midwest Exchange Scholarship, University of Kansas (2001 – 2005)
Dean's List, University of Kansas, UNMC College of Dentistry

PUBLICATIONS

Hansen PA, Gist J. A quick esthetic remount cast for all-ceramic restorations. J Prosthodont 2010;19:494-6.

Narayana N, Gist J, Smith T, Tylka D, Trogdon G, Wahl JK. Desmosomal component expression in normal, dysplastic, and oral squamous cell carcinoma. Dermatol Res Pract 2010;2010:1-8.