INTRAORAL CORROSION OF SELF-LIGATING METALLIC BRACKETS AND ARCHWIRES AND THE EFFECT ON FRICTION

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by
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INTRAORAL CORROSION OF SELF-LIGATING METALLIC BRACKETS AND ARCHWIRES AND THE EFFECT ON FRICTION

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University of Missouri-Kansas City, 2014

ABSTRACT

The purpose of this study was to investigate how the frictional coefficient was affected due to intraoral use. A secondary aim of this study was to determine whether or not there was a relationship between corrosion of orthodontic alloys and friction via scanning electron microscopic qualitative analysis. Orthodontic brackets and 0.019 x 0.025 inch stainless steel archwires were collected and divided into three groups of n=10: used bracket and used wires (UBUW), used brackets and new wires (UBNW), and new brackets and new wires (NBNW). 'New' materials were as-received from the manufacturer, and 'used' materials were clinically used bracket and wires collected from patients following orthodontic treatment. Archwires were pulled through bracket slots at a rate of 0.5mm/min while friction forces were measured. Following a cleaning process, the surface topography of the bracket slots was examined under a scanning electron microscope (SEM).

Based on a 1-factor MANOVA, there was no significant group effect (all $p>0.05$) on frictional forces. Partial eta squared values indicated that intraoral exposure had only a small effect on frictional forces ($\leq 3\%$). Qualitative analysis of SEM images did not show an association between surface characteristics of the bracket slots and magnitude of frictional force.

Results suggest that surface corrosion from intraoral use does not significantly affect friction at the bracket wire interface.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Dentistry, have examined a thesis titled "Intraoral Corrosion of Self-ligating Metallic Brackets and Archwires and the Effect on Friction" presented by Lori Lynn Tima, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

INTRODUCTION

Orthodontic treatment is based on the principle that if prolonged pressure is applied to a tooth, the bone surrounding the root will remodel and tooth movement will occur (Proffit WR, 2007a, 331). In orthodontics, brackets and wires come together to create a mechanical force in order to move teeth through the alveolar bone. During orthodontic space closure with sliding mechanics following premolar extraction, frictional forces are generated at the bracket-archwire interface. The magnitude of friction is a product of the normal (perpendicular) force component and the coefficient of friction at the bracket-archwire interface. The normal force is the force component which acts perpendicularly to the direction of desired movement (Olson et al. 2012).

These forces occur as a consequence of the moments generated due to loads that are not applied to the center of resistance of the tooth. The consequential moments are offset by couples generated at the bracket-archwire interface. Mechanical couples usually exist around all 3 axes of a tooth. When an archwire is ligated in a bracket slot, perpendicular forces potentially exist between the wire and the occlusal, gingival, and lingual surfaces of the bracket slot, between the ligature and archwire, and also differentially at the mesial and distal edges of the bracket when the bracket is tipped, causing binding of the wire. In clinical situations when restriction of sliding movements between the bracket and archwire are desired, friction is an asset. When attempting to move teeth using sliding mechanics, friction is an encumbrance (Olson et al. 2012).

Friction

Friction is the resistive force between two or more surfaces that opposes motion (Burrow 2009). There are two types of friction: static and kinetic. Static friction opposes the applied force, where its magnitude equals the amount of friction needed to prevent motion between two surfaces. As applied force increases, eventually there will be a point at which static friction is overcome and movement begins. Kinetic friction then opposes continuation of the movement (Burrow 2009). In orthodontics, kinetic friction is usually not a concern because continuous tooth movement along an archwire never occurs. During sliding mechanics, for instance retracting a canine back to fill the space after extraction of the first premolar, a quasi-static thermodynamic process is created. This means that the process occurs slowly, undergoing a sequence of states that are near equilibrium (Burrow 2009).

Orthodontic brackets are attached to teeth, which creates a system of interactions involving teeth, periodontal ligaments, alveolar bone, and archwire. The bracket moves relative to a wire in the bracket slot as the tooth moves through bone (Burrow 2009). Biologically, this process stimulates a series of protein up-regulations, which in turn stimulates bone deposition in areas of tension and bone resorption in areas of compression. Mechanically, this process involves a balance of motion and friction which result in the movement of teeth into the desired positions.

The friction between orthodontic brackets and archwires as-received from manufacturers, as well as the effects of different types of ligation systems have been studied extensively (Kusy and Whitley 1990; Henao and Kusy 2004; Marques et al. 2010; Kao et al. 2011; Tecco et al. 2011). A number of factors have been suggested to influence frictional resistance, including bracket material, wear of the wire, bracket width, interbracket distance, archwire material, diameter, wire stiffness, active torque, surface roughness, sliding velocity, and method of ligation (Khambay et al. 2004). In this study, we will focus on surface roughness and its effect on friction.

Bracket ligation is a crucial concept in orthodontic mechanics. Ligatures constrain the archwire in the bracket slot. Since ligation can determine to some degree the magnitudes of normal forces on a wire, it is ideal in some circumstances that ligation forces are minimized to decrease friction between the bracket and archwire during some techniques such as sliding mechanisms. Conversely, ligation forces can be maximized to produce a high friction bracket-archwire relationship if full engagement and minimal movement between the bracket and wire are desired (Iwasaki et al. 2003).

The three elemental methods of constraining the wire in the bracket slot are elastomeric, steel tie, or self-ligating mechanisms. When considering the keys to ideal ligation for sliding mechanics, conventional ligation using elastomeric or stainless steel ties have many shortcomings. Therefore, manufacturers and clinicians have worked to minimize friction at the bracket-archwire interface by designing brackets that eliminate the need for traditional elastomeric or stainless steel tie ligatures. Friction associated with elastomeric ligatures is nearly 30 to 50 percent greater than that associated with stainless steel ties and self-ligating mechanisms (Shivapuja and Berger 1994). Furthermore, these ligatures lose dimensional stability and decrease force levels when exposed to moisture and heat. Studies have demonstrated a rapid force loss of 53 to 63 percent in 24 hours (Taloumis et al. 1997).

Unlike elastomeric ligatures, loosely tied stainless steel ligatures have exhibited negligible friction in both wet and dry states (Hain et al. 2003). This characteristic creates an environment with minimal friction along the archwire. However, there is great variance in tightness of wire ligation amongst clinicians, creating an unpredictable anchorage situation (Iwasaki et al. 2003).

Since the early 1980s, there has been a surge in the number of self-ligating or ligature free brackets (Harradine 2003). Today's market demands are forcing manufacturers to continually redesign their bracket ligation apparatus to maintain an edge on the competition (Burrow 2009). An increasing number of in vitro studies involving these newly designed brackets have sparked much discussion over which bracket design provides the most friction reduction. Self-ligating bracket systems use a mechanical device, such as a "door" built into the bracket, which is capable of converting the bracket slot into a rectangular tube. Although they are often referred to as one group, self-ligating brackets are actually quite dichotomous. These brackets can more accurately be divided into active and passive systems. Active designs contain a spring clip that makes positive contact with the archwire whereas the passive self-ligating system has a door that does not actively press the archwire into the bracket slot. A substantial reduction in frictional resistance was noted when elastomeric ligation was compared to passive (decrease of 75%) and active (decrease of 50%) self-ligations systems (Krishnan et al. 2009).

Orthodontic Alloy Corrosion

Because brackets and archwires are exposed to the oral cavity for a significant period of time (about two years for brackets and at least three months for finishing wires), corrosion of the associated alloys is a topic of interest. The harsh oral environment initiates corrosion of the alloys used in orthodontics which alters the surface topography as well as the chemistry of the wire-bracket interface, thus, changing the coefficient of friction. As the surface becomes more irregular, the frictional coefficient increases (Ribeiro et al. 2012). Loreille (2002) claimed that one of the main reasons for the unpredictable control of orthodontic forces may be the surface corrosion of brackets and wires (Loreille 2002). The presence of a third body such as debris produced by wear or corrosion products at the bracket/archwire interface can alter the initial friction contact conditions (Al-Khatib et al. 2005). When brackets or wires are evaluated after clinical use, studies have shown surface modifications with signs of corrosion, wear, and plastic deformation when compared to bracket or wires as-received from manufacturers (Regis et al. 2011).

Archwires have been retrieved from orthodontic patients and evaluated for signs of corrosion. Like the retrieved brackets, archwires used *in vivo* showed significant wear. Under scanning electron microscopy (SEM) analysis, grooves and striations parallel to the long axis of the wire, scratches perpendicular to the long axis of the wire, and pitting were all seen on some or all of the archwires examined (Daems et al. 2009). Further analyses have also revealed crevice corrosion at irregularities caused by bracket-wire contact areas and manufacturing processing (Daems et al. 2009). Daems et al. (2009) found four types of corrosion patterns on clinically used stainless steel wires. All wires exhibited the first type of corrosion pattern: grooves and striations parallel to the long axis of the archwire resulting from the sliding/drawing process (Daems et al. 2009). Some samples of wires showed the second type of corrosion pattern: grooves and striations not parallel to the long axis of the archwire which can be related to an occasional mechanical impact produced during cutting or holding the wire with orthodontic instruments. Pitting was the third type of pattern observed which resulted from a chemical interaction. Finally, surface defects due to plastic deformation were detected as well. A gradient in oxygen across these areas is most probably the origin of this degradation process (Daems et al. 2009).

Metal surfaces are attacked unevenly due to factors such as the nature of the alloy or inclusions and impurities (Graber 2000). The initial pits caused by chemical attack develop into crevices, which weaken the mechanical properties of the metal. After a pit forms, it limits the access of oxygen thus hindering the regeneration of the chromium oxide protective layer on the steel. This causes the pH inside the pockets to decrease and the process becomes autocatalytic, undermining the internal structure of the metal with deep cavities or fissures (Graber 2000).

Intergranular stress corrosion cracking can result from a combination of susceptible material, critical environment, and sufficient mechanical driving force (Rahimi et al. 2009). Resistance to intergranular corrosion and stress corrosion cracking can be improved through specific thermo-mechanical manufacturing processes which aim to prevent the initiation and propagation of intergranular degradation along grain boundaries (Jin et al. 2010). This is done by introducing coincidence site lattice (CSL) boundaries into the grain boundary networks (Jin et al. 2010). Processing typically involves sequential annealing and cold deformation cycles however, variations in processing can have a dramatic effect on the grain boundary, thus, compromising the integrity of the grain boundaries (Jones et al. 2009). In austenitic stainless steels, sensitization of grain boundaries can lead to cracking (Rahimi et al. 2009).

Another type of corrosion encountered in orthodontics is corrosion induced by microorganisms such as sulfate-reducing *Bacteroides corrodens* and acid-producing *Streptococcus mutans*. This phenomenon is not well understood, but symmetric, round craters are seen in corroded bracket bases contaminated with microorganisms under magnification (Graber 2000).

Stainless Steel Chromium Protective Layer

Stainless steel is the most common alloy used in orthodontics today. This alloy has good biocompatibility and high corrosion resistance in the oral environment. Since the 1950s, type 300 series of stainless steel alloys have been used in the manufacture of most orthodontic brackets. These typically contained 17-25% chromium and 5-25% nickel, with the balance being iron (Kusy and Whitley 1997). Orthodontic stainless steel wires today are generally made of austenitic stainless steel composed of approximately 18% chromium and 8% nickel (Chaturvedi and Upadhayay 2010). Chromium, a highly reactive base metal, gives stainless steel its resistance to corrosion. When at least 10-13% chromium is present, a coherent oxide layer forms that passivates the surface, thereby rendering the alloy "stainless" (Flinn et al. 1975). Therefore, a common requirement for all grades of stainless steels is that the chromium content must be greater than 11% (wt.) in the composition. This is the minimum amount of chromium that is able to maintain the stainless appearance by forming a compact chromium-rich ultrathin surface oxide or "passive film" (Castle et al.1990). Oxygen is needed to form and maintain the film (Chaturvedi and Upadhayay 2010). Stainless steel is most vulnerable to dietary chloride ions which are able to breach the passive film on the orthodontic wire. Aside from the salty foods people consume, chloride ions at levels more than 500 mg/L are found in saliva. The passivated film is also at risk when exposed to other aggressive substances such as organic acids produced by food decomposition and the sulfated compounds found in saliva (Graber 2000).

In an experiment by Shahabi et al. (2011) changes in orthodontic brackets in terms of decrease in the mean weight were demonstrated after 6 weeks of immersion in artificial saliva mixed with acidic food such as coca cola®, vinegar, and lemon juice. Results showed a net weight loss of 0.031 g for coca cola®, 0.009 g for vinegar, and 0.007 g for lemon juice (Shahabi et al. 2011).

Metal Ion Release

Performance of alloys used in brackets and archwires placed in the oral cavity has been a major concern in previous years (Eliades et al. 2002). In orthodontics, metallic brackets remain in a buccal environment for one to three years, and are exposed to changes in pH, temperature, and mechanical loads (Ribeiro et al. 2012). Typically, metals used in orthodontics are composed of alloys which may include a combination of nickel, chromium, cobalt, iron, molybdenum, and titanium (Regis et al. 2011). Studies have shown that as an alloy undergoes degradation in artificial saliva, metal ions are released to some extent causing changes in the surface topography (Lin et al. 2006). The ions released from stainless steel alloys are mainly iron, nickel, and chromium. The release of these ions in artificial saliva are five- to seven- times higher than that of those in saline solutions (Brune 1986; Kerosuo et al. 1995). Although all three ions may have adverse effects, nickel has received most of the attention due to its reported potential to produce allergenic effects (Oh and Kim 2005). The potential hazard associated with this phenomenon is the cytotoxicity of the ions released (Guyuron and Lasa 1992). However, studies suggest that the metal ion release from stainless steel orthodontic brackets in acidic solution should not be cause for concern (Staffolani et al. 1999) given that the total ions released after 12-week immersion in artificial saliva does not exceed recommended daily intake (300-500 μg) (Huang et al. 2001).

Effect of Fluoride on Stainless Steel

In the oral environment, fluoride-containing commercial mouthwashes, toothpastes and prophylactic gels are widely used to prevent dental decay and reduce dental sensitivity due to exposed tooth root surfaces. The fluoride levels in the oral cavity vary according to different prophylactic treatments. Fluoride is used at concentrations of up to 1% in toothpastes and mouthwashes. Two-percent concentrations are used when the aim is to eliminate enamel stains. These substances have a pH range of 3.5 to 7.0 (Arends and Christoffersen 1990). Kao and Huang showed that after immersion of orthodontic brackets in artificial saliva with NaF added, bracket surface defects and pitting were observed (Kao and Huang 2010).

Corrosion and Friction Studies

In order to study corrosion of orthodontic metal alloys, researchers often use saliva to mimic the oral environment. Although this simulated environment has allowed specific parameters to be estimated, it lacks a clinical representation of the complexity of the oral environment (Regis et al. 2011). The effect of aging, or the length of time an alloy is exposed to the oral environment, is an important factor to consider regarding orthodontic mechanics and its efficacy (Marques et al. 2010). There are many aspects of the oral environment that cannot be adequately replicated *in vitro*. This would include factors such as variations in pH caused by diet, decomposed food debris, temperature changes, masticatory forces, oral flora and their byproducts and multi-axial loads from activation of the wire in the bracket slot (Regis et al. 2011).

Some authors have used brackets retrieved from patients who have completed orthodontic treatment to see how friction was influenced after exposure to the oral environment. Because of the variable results among studies, the true impact of the oral environment on friction of orthodontic alloys remains somewhat inconclusive. Ribeiro et al. (2012) found that frictional resistance increased from 21.22 +/- 1.66 g in as-received brackets to 32.91 +/- 1.36 g in retrieved brackets, a mean increase of 55 percent after intraoral corrosion (Ribeiro et al. 2012). Regis et al. (2011) showed that although there was a difference in the sliding resistance at the bracket-archwire interface, there were large standard deviations (i.e. +/-36.50%) for each bracket tested (Regis et al. 2011). The authors performed friction tests using as-received 0.019 x 0.025 in stainless steel archwires. When using this particular wire in orthodontic treatment, the same archwire sometimes is used in the patient for several months.

Kao et al. studied frictional resistance after immersion of metal brackets and orthodontic wires in a fluoride-containing prophylactic agent and an artificial saliva pH 6.75 solution (Kao et al. 2006). Brackets and stainless steel wires were immersed in 0.2% Acidulated Phosphate Fluoride (APF), or the pH 6.75 solution for 24 hours and friction was tested. Results showed that frictional resistance of the brackets and wires increased after exposure to 0.2% APF. A larger frictional force was recorded for the pH 6.75 group than the APF group.

As discussed previously, archwires show significant wear and tear after being used in treatment. Clinically applicable and significant results are likely when testing for changes in friction using both retrieved brackets and retrieved archwires.

Marques et al. (2010) used brackets and archwires, which is important when analyzing true effects of oral environment induced corrosion on frictional resistance during sliding mechanics. Marques et al. (2010) attempted to measure the effects, but the results were difficult to extrapolate to the clinic because the experimental protocol limited bracket and wire exposure to 8 weeks in the oral cavity. Most orthodontic treatment is at least two years in length (Marques et al. 2010). Furthermore, three brackets were placed on a molar, second premolar, and first premolar so that the wire could be immediately placed passively in the aligned bracket slots. This means that there was no tooth movement and no known mechanical strains applied to the wire. Nevertheless, it was reported that there was a significant (20.8%) increase in friction after eight weeks of intraoral exposure (Marques et al. 2010).

Problem Statement

To date, no study has evaluated clinically used orthodontic brackets and archwires for the differences in friction compared to pristine materials.

The purpose of this study was to investigate how the frictional coefficient was affected due to intraoral use. A secondary aim of this study was to determine whether or not there was a relationship between corrosion of orthodontic alloys and friction via scanning electron microscopic qualitative analysis.

Hypotheses

1. Frictional force of the bracket/wire system will significantly increase with exposure to the oral environment.
2. There will be a qualitative difference in the surface topography of brackets and wires as a function of exposure to the oral environment.

CHAPTER 2

METHODS AND MATERIALS

Specimen Preparation

Used orthodontic archwires and brackets were collected from patients after completion of orthodontic treatment at University of Missouri at Kansas City (UMKC) School of Dentistry (AHSIRB #13-10—Non-human subject research). No patient identifiers were associated with recovered materials. Care was taken to not distort the bracket slot during debonding. Brackets and archwires were removed from patients as one unit, leaving the brackets engaged on the wire. Each set of debonded brackets and archwires were wiped down with alcohol-soaked gauze to sanitize them. They were then stored in individual plastic bags[1] of distilled water and were exposed to 15 minutes of ultrasonic cleaning device[2]. This allowed organic matter to be removed without affecting corrosion through exposure to cleaning chemicals. All brackets were then removed from the archwire and only premolar brackets were kept for use in the study. Limiting analysis to premolar brackets minimized the variability in friction testing due to differences in bracket widths. Following ultrasonic cleaning, the archwires and premolar brackets were again wiped down with alcohol-soaked gauzed to clear off any loose debris and to dry, after which they were then placed into dry sterilization pouches[3] and stored at room temperature until the day of testing. Any premolar bracket with clinically visible damage to the slot due to debonding procedures was eliminated from the study. The used premolar brackets were kept with the used archwire for each patient. Brackets and wires received from the manufacturer underwent the same preparation process as the retrieved brackets and wires: wiping

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[1] Ziploc SC Johnson, 1525 Howe Street, Racine, WI 53403
[2] Dentronix DDUS 60R, Dentronix Orthodontic Products, 235 Ascot Parkway, Cuyahoga Falls, OH 44223
[3] Assure Plus, Sultan Chemists, Inc. 85 West Forest Avenue, Englewood, NJ 07631

down with alcohol-soaked gauze, ultrasonic cleaning, wiping down with alcohol-soaked gauze a second time, and storing in a dry sterilization pouch.

Bracket Characteristics

Maxillary and mandibular first and second premolar brackets[4] with slot size 0.022 x 0.028 inch and mesio-distal width of 2.9 mm were used in this study. These were self-ligating brackets each with a passive slot door. The bracket prescriptions were -12 degrees torque and +4 degrees tip for lower first premolar brackets, -17 degrees torque and +4 degrees tip for lower second premolars, and -11 degrees torque and +2 degrees tip for upper first and second premolar brackets. A negative torque would clinically move the root of the tooth labially and a positive tip would move the root of the tooth distally relative to the crown.

These brackets were selected because of the self-ligating components which eliminated the variable effects of steel or elastic ligatures on friction. The brackets recovered from patients in this study remained in the mouth for 22 months on average.

Wire Characteristics

0.019 x 0.025 inch stainless steel archwires[5] were the finishing wires examined and tested in this study. As well as as-received wires, archwires were collected that had been used clinically for several months. The average time of intraoral exposure for the recovered wires was 12 weeks.

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[4] Damon, Ormco Corporation, 1332 S. Lone Hill Ave., Glendora, CA 91740

[5] Syron Dental Specialties, Ormco Corporations, 1332 S. Lone Hill Avenue, Glendora, CA 91740

Mechanical Friction Testing

A universal mechanical testing machine was used to test frictional forces as straight segments of 0.019 x 0.025 inch stainless steel archwires were pulled through the slots of brackets bonded onto glass slides inserted into a custom mounting jig (fig. 1).

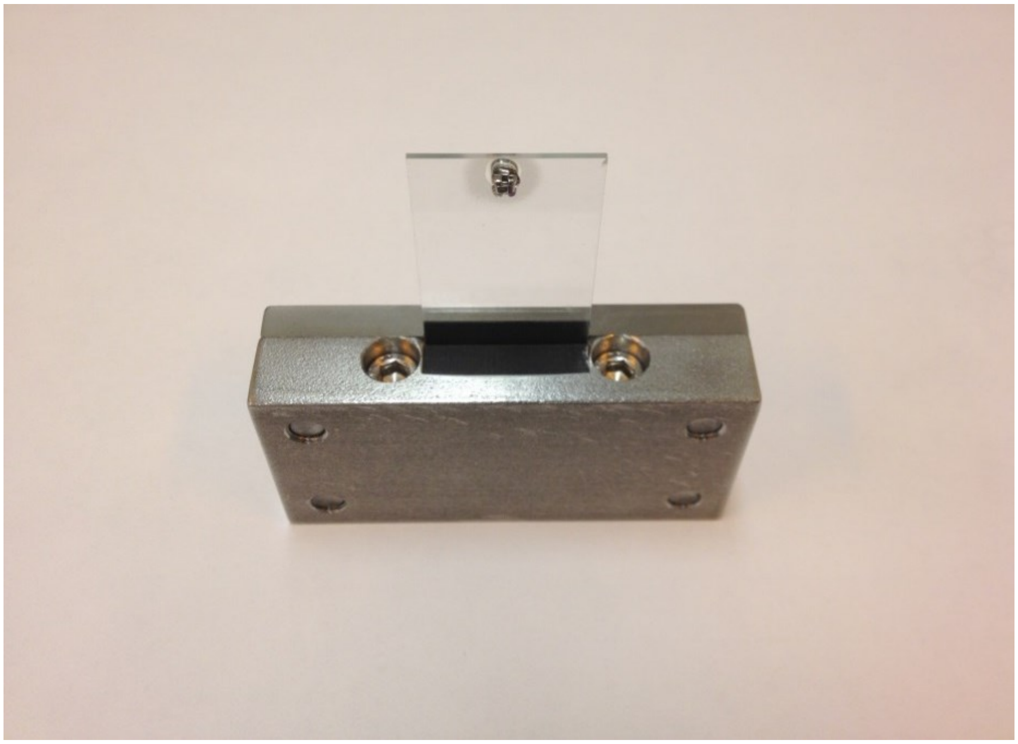

Figure 1. Custom mounting jig with glass slide inserted

To obtain the straight segments of the 0.019 x 0.025 inch archwires, the wire was cut 5 mm beyond the point where it began to curve. The curved portion was used to bend a small loop, taking care to not disturb the properties of the straight portion. The loop was used as an attachment for the load cell of the testing machine (fig. 2). A glass slab was used to check for straightness of the wire segment. If the wire did not lay flat on two sides, it was excluded from use in the study.

It was important that brackets were mounted with the slot perpendicular to the floor in order to prevent a binding effect as the archwire segment was drawn through the slot. To obtain this, 0.021 x 0.025 inch stainless steel straight wires[6] and custom parallel mounting templates were used to align the bracket slots (fig. 3).

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[6] Syron Dental Specialties, Ormco Corporations, 1332 S. Lone Hill Avenue, Glendora, CA 91740

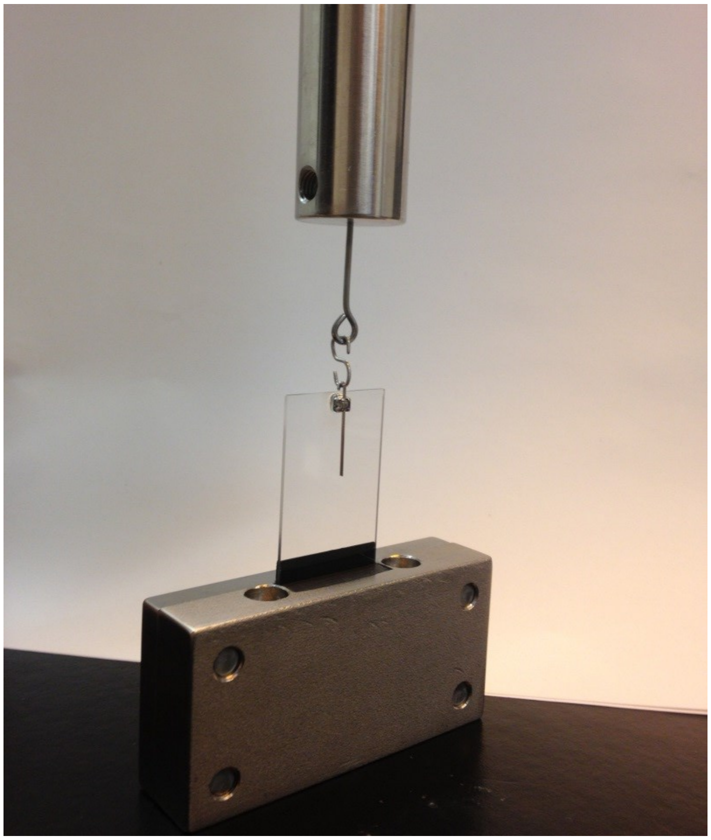

Figure 2. Attachment of archwire segment to testing machine via ‘S’ hook. The archwire segment is ligated to the bracket which is mounted on the glass slide.

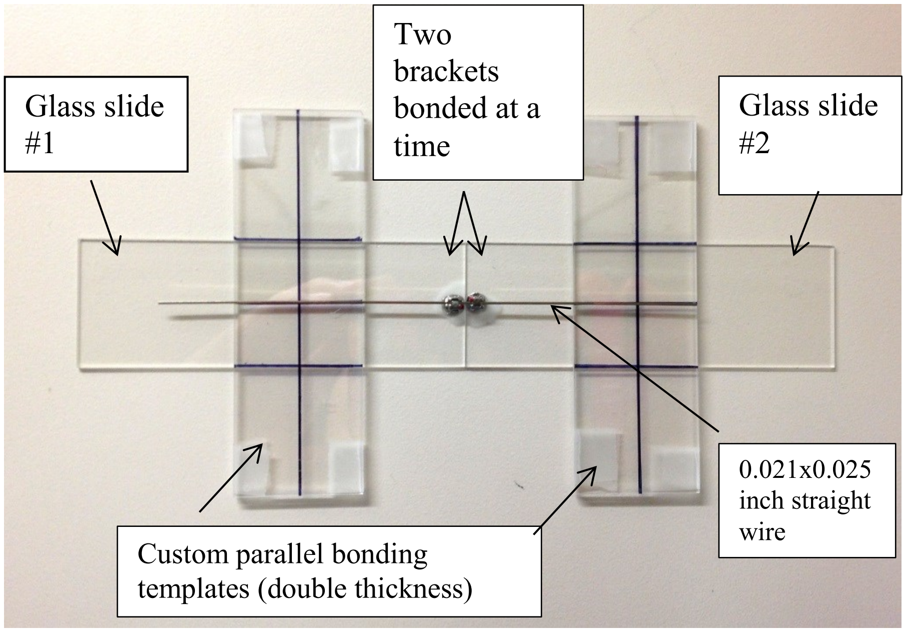

Figure 3. Custom templates for bonding brackets to glass slides

Two bracket-glass slide test specimens were bonded at the same time. The 0.021x0.025 inch straight wire was placed into the slots of two brackets with the self-ligating doors closed to engage the wire into the slot. Each glass slide was prepared by micro-etching with aluminum oxide air abrasion the estimated area where the bracket would be mounted. Then, the two glass slides were lined up length-wise, with etched surfaces toward each other (fig. 3). To set up for the bonding, custom parallel bonding templates were made by taping two glass slides together to double the thickness, and by drawing lines on them to allow for parallel positioning of the straight wire above the etched areas. These templates were laid on the two aligned glass slides, and then the straight wire was positioned on top of the templates so it was centered over the micro-etched areas and parallel to the long edges of the glass slides (fig. 3). The two brackets were slid along the straight wire until they were one millimeter from the short edge of the glass slide and centered over the micro-etched areas (fig. 4). The double thickness of the templates allowed the brackets to remain suspended off the etched mounting surface thus eliminating expression of the tip and torque prescriptions which were built into the bracket base (fig. 4). This process ensured that each bracket slot was mounted uniformly parallel with the long edge of the glass slide, thus minimizing variability during friction testing.

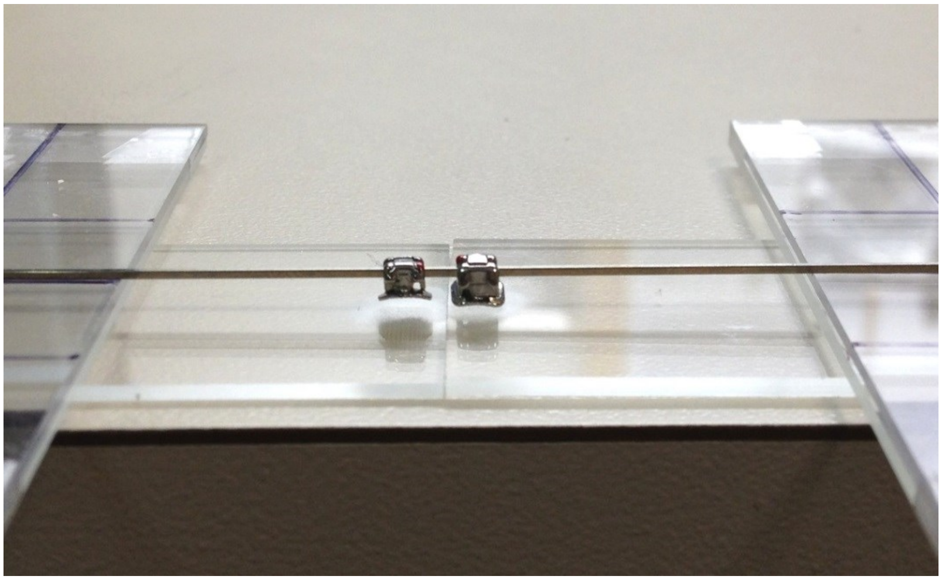

Figure 4. Brackets suspended on straight wire. The wire rests on two custom bonding templates (right, left) above the glass slides opposite micro-etched areas

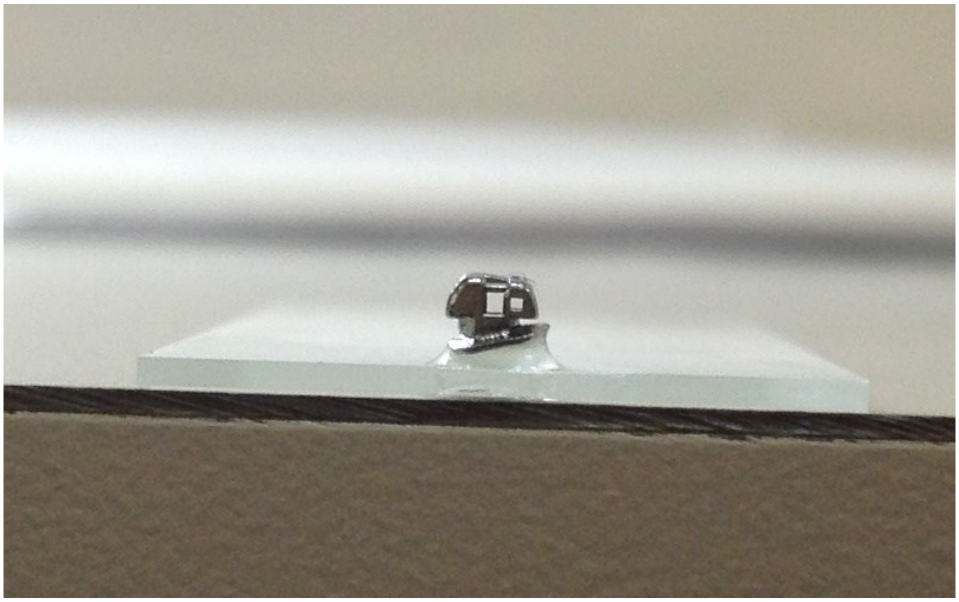

Figure 5. Epoxy fills space between bracket base and mounting glass

Five minute epoxy[7] was mixed and then placed on the pads of the brackets. The space between the bracket base and the glass slide was filled by this epoxy (fig. 5) which, after setting, could hold the bracket at that position. The two brackets were placed facing opposite ways allowing even weight distribution thus preventing any tipping of the straight wire while the epoxy was setting. There was a minimum setting time of 24 hours for the epoxy before any friction testing was done.

Each sample/specimen for testing consisted of a glass slide with the bracket mounted one millimeter from the edge. A straight segment of 0.019 x 0.025 inch stainless steel archwire was placed in the bracket slot. The glass slide with the bracket attached was inserted into the custom mounting jig (fig. 1), which was then secured in a waterbath (fig. 6) and connected to the upper arm of an universal mechanical testing machine[8] using an ‘S’ hook (fig. 2).

Once each bracket was mounted onto a glass slide, the glass slide was inserted into the custom mounting jig (fig. 1). The glass slide was inserted into a slot in the mounting jig sandwiching it between a thin plastic chip on one side and a thicker plastic block on the other thus preventing the glass from contacting any stainless steel surfaces, allowing for better grip and the ability to put pressure on the glass surface without any cracking. The glass slide was held in the slot by four screws pressing against a plastic block. The mounting jig was then screwed into the base of the waterbath. The waterbath was filled with distilled water set at 37 degrees Celsius in order to create a wet environment simulating intra-oral temperature (fig. 6). The wire segment with the curved end bent into a loop was placed in the bracket slot and the door of the bracket was closed engaging the wire into the slot. The loop was connected to an ‘S’ hook which was

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[7] Loctite Epoxy, Henkel Corporation, One Henkel Way, Rocky Hill, CT 06067

[8] Model 5967R4163, Instron Industrial Products, 825 University Ave, Norwood, MA 02062

connected to the upper arm/load cell of the testing machine (fig. 2). This allowed some swivel capabilities to eliminate binding at the bracket slot/archwire interface.

The testing machine was set to pull each 0.019 x 0.025 inch wire segment through the bracket slot at 0.5 mm per minute for 5 millimeters while frictional resistance forces were measured in newtons (N). The load cell registered the force levels as the wire moved through the bracket slot, and these values were stored on a computer hard disk. Raw data collected[9] at a rate of 10 Hz over a period of 10 minutes resulted in 6000 data points.

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[9] Bluehill® 2 software program, Instron USA, 825 University Ave., Norwood, MA, 02062

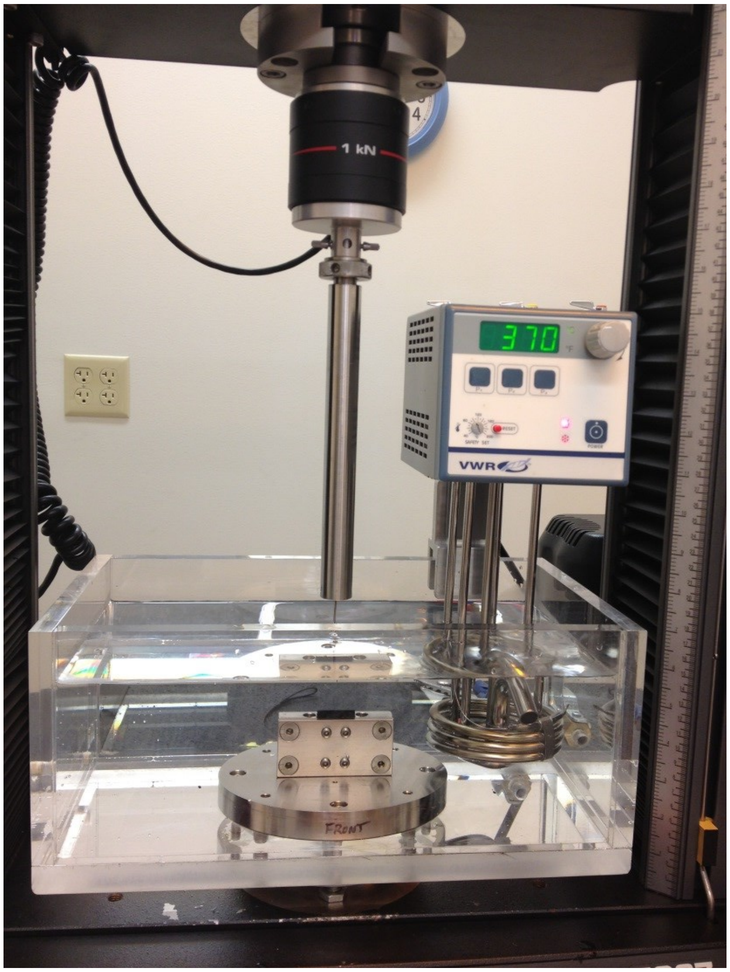

Figure 6. Universal mechanical tester with 37º waterbath

Experimental Design

This *in-vitro* experimental design tested intergroup differences in friction. As described above, instantaneous frictional forces (N) were measured at a rate of 10 Hz and rectified over a 10 minute period, resulting in 6000 data samples (fig.7). Slip-stick/static frictional effects were identified by averaging the maximum 10% of rectified data. Overall frictional effects were determined by averaging all rectified data over the 10 minute recording period. Table 1 displays the groupings used in friction testing.

Sample Size

This being a pilot study, convenience sample sizes of n=30 brackets and n=30 wires were used. These can further be broken down into n=10 as-received brackets, n=20 clinically used brackets, n=20 as-received wires, and n=10 clinically used wires. There were ten brackets and ten wires in each of the three groups for the friction testing (Table 1): Group 1: new (as-received) brackets and new wires (NBNW), Group 2: used brackets and new wires (UBNW), Group 3: used brackets and used wires (UBUW).

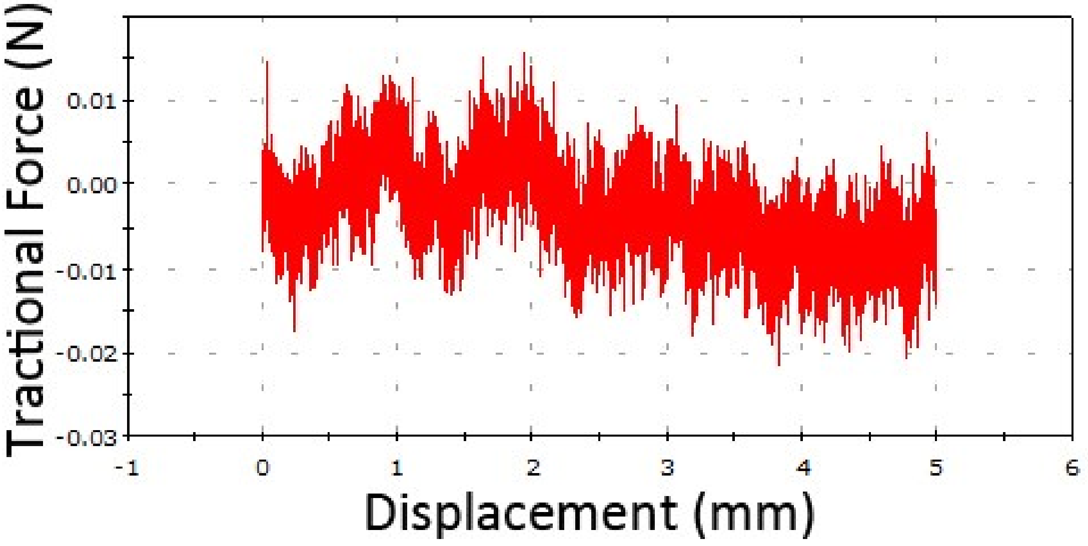

Figure 7. Raw data showing 6000 data points

TABLE 1

GROUPS IN RESEARCH DESIGN

	New Bracket	Used Bracket
New Wire	X (NBNW)	X (UBNW)
Used Wire		X (UBUW)

These groups were chosen because they represent three time points during orthodontic treatment. Brackets remain in the mouth throughout the entire orthodontic treatment, however wires are changed out frequently as progression moves from flexible wires (e.g. nickel titanium or braided stainless steel) to more rigid stainless steel wires until the finishing wire is placed in the mouth. The finishing wire is most commonly a 0.019 x 0.025 inch stainless steel wire in bracket slot size of 0.022 x 0.028 inch and this same wire can remain in the mouth for several months allowing for corrosion to occur.

Following friction testing, all brackets were cleaned in preparation for scanning electron microscopy imaging. The cleaning process involved blowing compressed air on the bracket focusing on the bracket slot, then dunking the glass slide with bracket attached into a falcon tube[10] of ethanol followed by another round of compressed air until dry. The specimens were then placed into an air-tight plastic container.

SEM Evaluation

Following friction testing, scanning electron microscopy (SEM)[11] was used to analyze qualitatively the surface topography of the bracket slot. Assessments of surface corrosion of the slots of the premolar brackets collected from patients as well as new brackets, as-received from the manufacturer, were performed.

Surface topography of three specimens from each test group was evaluated. Specimens were chosen based on frictional force data: the bracket which had the least amount of friction, the bracket that had the most amount of friction, and one bracket in the middle of the two extremes. Specimens were coated with a gold/palladium alloy and images were taken at 35X, 200X, 1000X, and 2000X. Three areas of the bracket slot were targeted for imaging in each

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[10] MIDSCI 280 Vance Rd St Louis, MO 63088

[11] Philips XL 30 ESEM-FEG, FEI Company, 5350 NE Dawson Creek Drive, Hillsboro, OR, 97124

specimen: the mesial or distal raised ledge of the slot base, a point in the middle 1/3 of the slot base, and one of the adjacent walls of the slot base. The inner surface of the self-ligating door of the bracket was not evaluated for evidence of corrosion. The SEM imaging table was tilted 10-30° to view the wall adjacent to the slot base.

Data Analysis

Statistical Analysis for Friction Differences

A one-factor multivariate analysis of variance (MANOVA) was used to test for significant differences amongst Groups 1 through 3. ANOVA was used to determine group differences in i) slip-stick and ii) kinetic friction effects. A Tukey post-hoc test was run. Effect size was calculated and, because this was a pilot study, a power analysis was performed at 0.80 significance.

SEM Qualitative Topographical Analysis

A qualitative analysis of the scanning electron microscopy images from each experimental condition was utilized to determine the general level of surface topography changes from corrosion. Used bracket slot surfaces were observed and compared to the slot surfaces of new brackets. Areas of debris, striations, and pitting corrosion were noted on used brackets. Three specimens within each of the three groups were evaluated via SEM analysis.

CHAPTER 3

RESULTS

Frictional Force

Friction testing was performed on each specimen and static friction was calculated from the average of the top 10% of the data points. The overall friction was calculated as an average of all data points. Overall and static means were reported in newtons for each of the three groups described in Table 1. The overall means were 0.0060 ± 0.0025 N, 0.0073 ± 0.0042 N, and 0.0063 ± 0.0035 N for NBNW, UBNW, and UBUW respectively (Table 2). Static means were 0.0138 ± 0.0045 N, 0.0154 ± 0.0056 N, 0.0174 ± 0.0149 N for NBNW, UBNW, and UBUW respectively (Table 2). The mean static and overall frictional forces and their standard deviations for each group of different bracket-wire combinations are summarized in figure 8.

Based on a 1-factor multivariate analysis of variance (MANOVA), there was no significant effect ($p>0.05$) of either of the three groups on overall ($p=0.713$) or static ($p=0.667$) frictional forces. The Tukey post-hoc test confirmed this reporting no significant difference in any combination of groups ($p>0.05$). A power analysis was run to determine a sample size that could provide statistically significant differences. Based on the power analysis for overall frictional forces, a sample size of more than 120 would provide a power of 0.806. For static force, a sample size of more than 145 would provide a power of 0.811. However, the partial eta squared values (effect sizes), which are independent of sample size, showed that small percentages of static (2.5%), and of overall (3%) frictional force means were attributable to intraoral exposure.

The mean resistive static forces increased from NBNW to UBNW to UBUW. However, mean resistive overall forces decreased slightly from UBNW to UBUW. Spikes in the frictional forces were recorded on several bracket/archwire combinations. One in particular, found in UBUW_1, was almost an order of magnitude larger than static frictional forces recorded for that specimen (fig. 9).

Smaller spikes in the frictional forces were found in other bracket/archwire combinations. Surprisingly, the second largest spike came from NBNW_12. All other spikes were found in the UBUW group. Figure 10 shows how these spikes compare to the largest spike in UBUW_1.

Scanning Electron Microscopy of Corrosion

When scanning electron microscopy imaging was viewed, there were notable differences between new brackets and clinically used brackets (fig. 11). Although each specimen underwent the same cleaning protocol, debris and dirt was found in the slot of all brackets. Used brackets retained large amounts of organic materials, as well as exhibiting corrosion.

Striations could be seen on both used and new brackets which could be wear tracks from friction testing or possibly marks made during the manufacturing process (fig. 12). Pitting corrosion and stress corrosion attacking grain boundaries was noted on retrieved brackets (fig. 13).

TABLE 2

STATISTICS OF FRICTIONAL FORCE FOR EACH BRACKET-ARCHWIRE COMBINATION

Group		Mean	Std. Deviation	n
Static	NBNW	0.0138	0.0045	10
	UBNW	0.0154	0.0056	10
	UBUW	0.0174	0.0149	10
	Total	**0.0155**	**0.0093**	**30**
Overall	NBNW	0.0060	0.0025	10
	UBNW	0.0073	0.0042	10
	UBUW	0.0063	0.0037	10
	Total	**0.0065**	**0.0035**	**30**

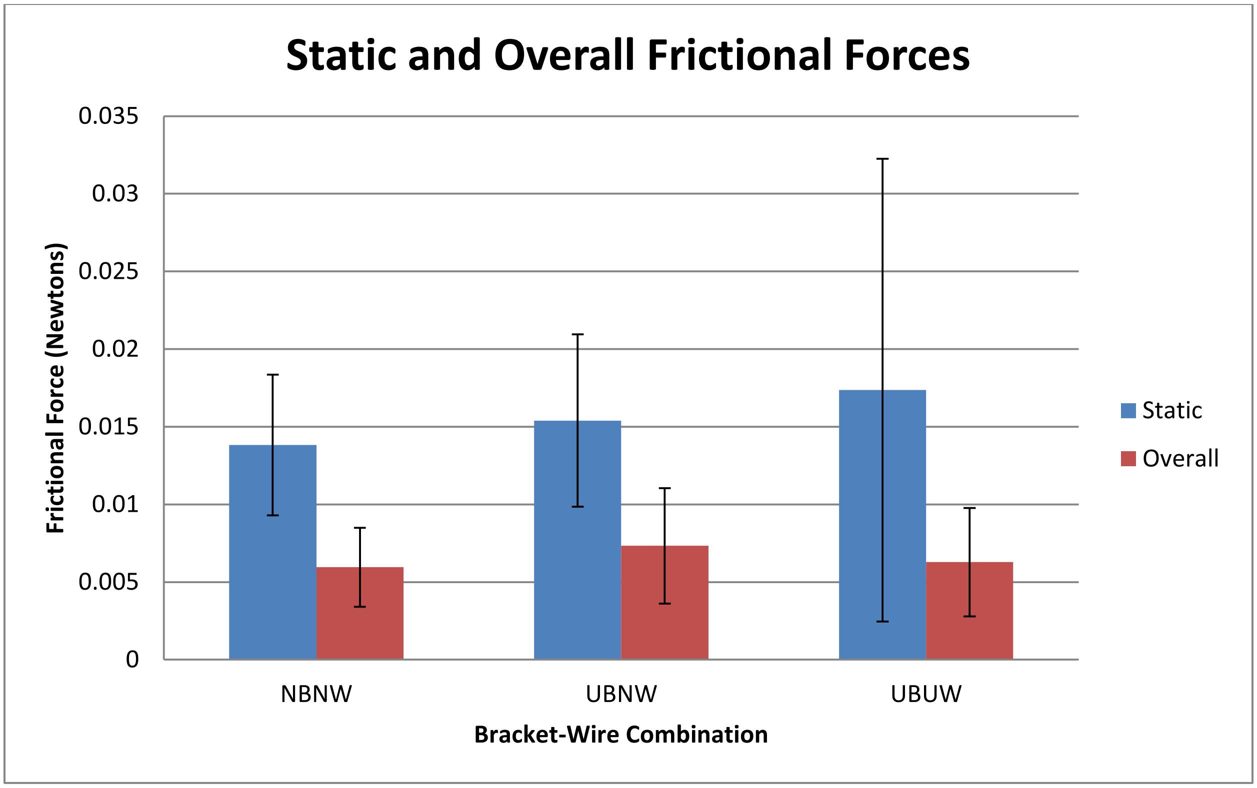

Figure 8. Mean Static and Overall Frictional Forces with Standard Deviations

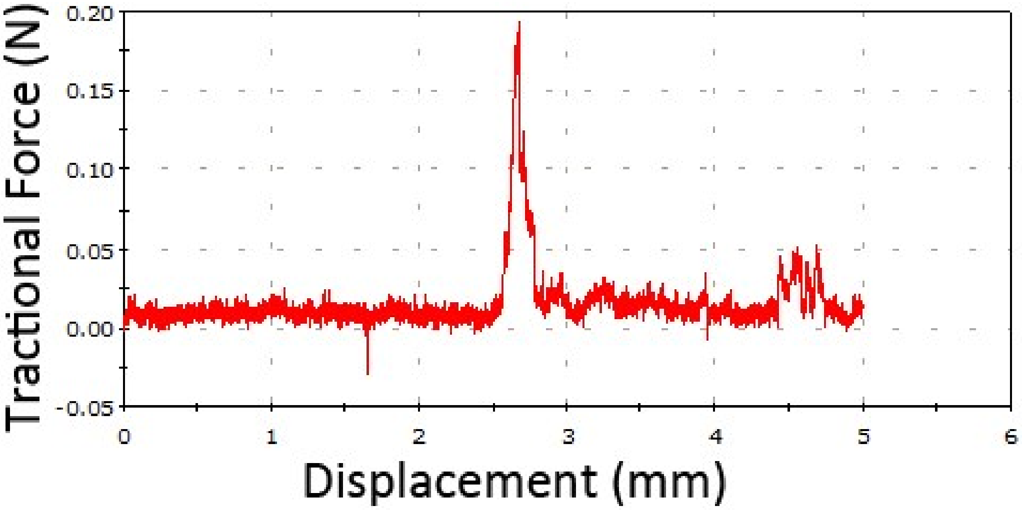

Figure 9. A spike in frictional force for UBUW_1. This spike is an order of magnitude larger than normal frictional force recording.

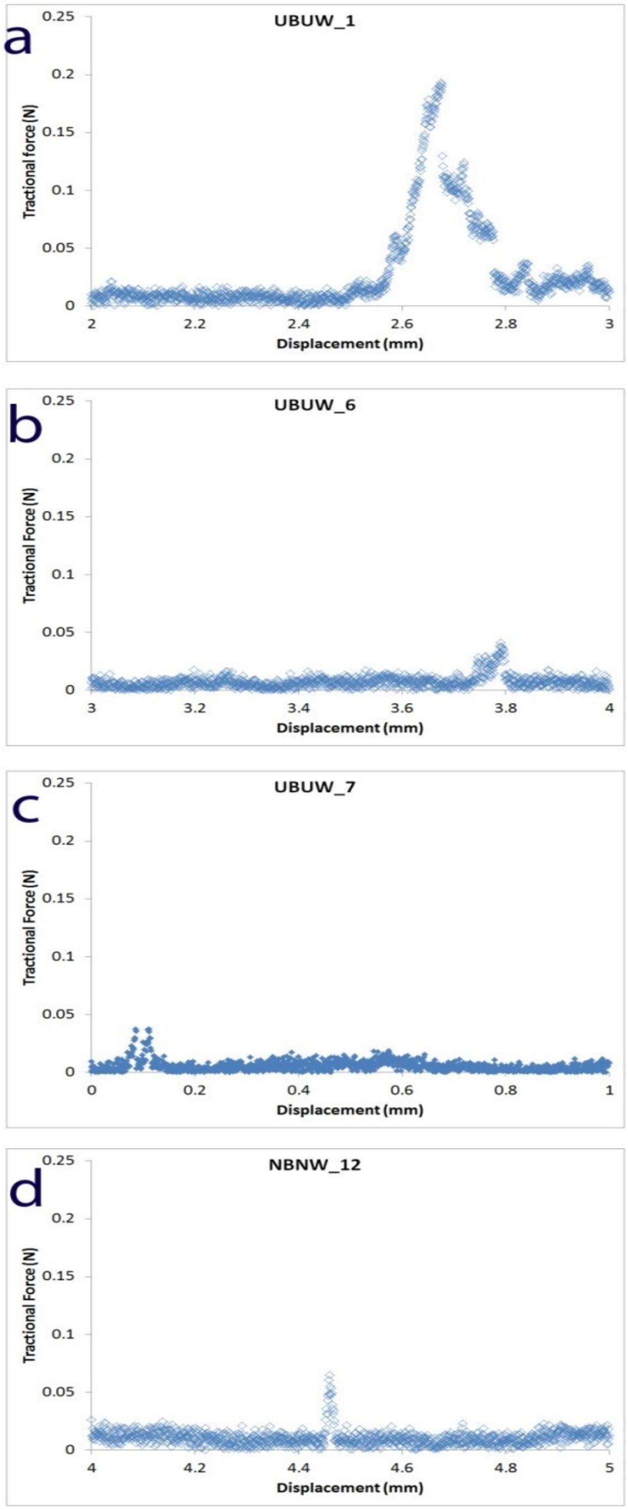

Figure 10. The four largest spikes in frictional forces compared in same-scale graphs.

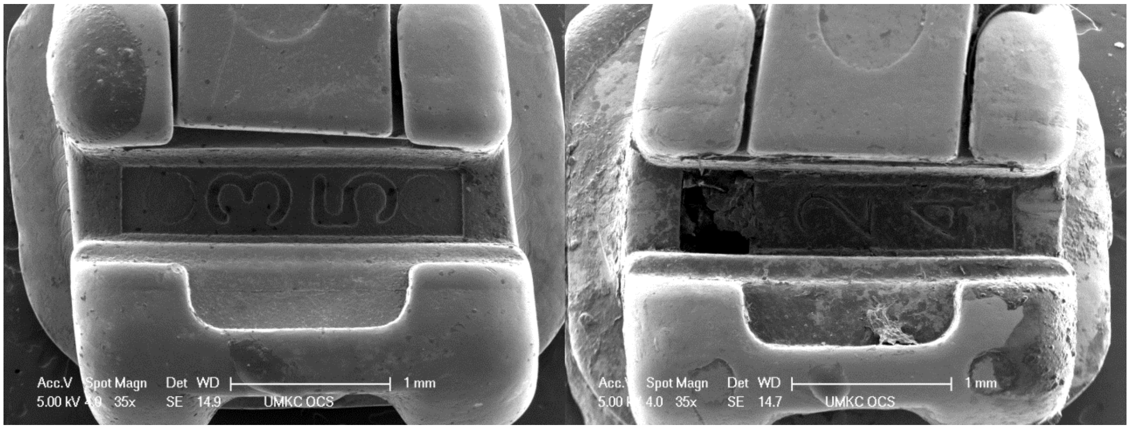

Figure 11. SEM images of an as-received and a retrieved bracket at 35x. Both the as-received bracket (left) and the retrieved bracket (right) images were taken following friction testing.

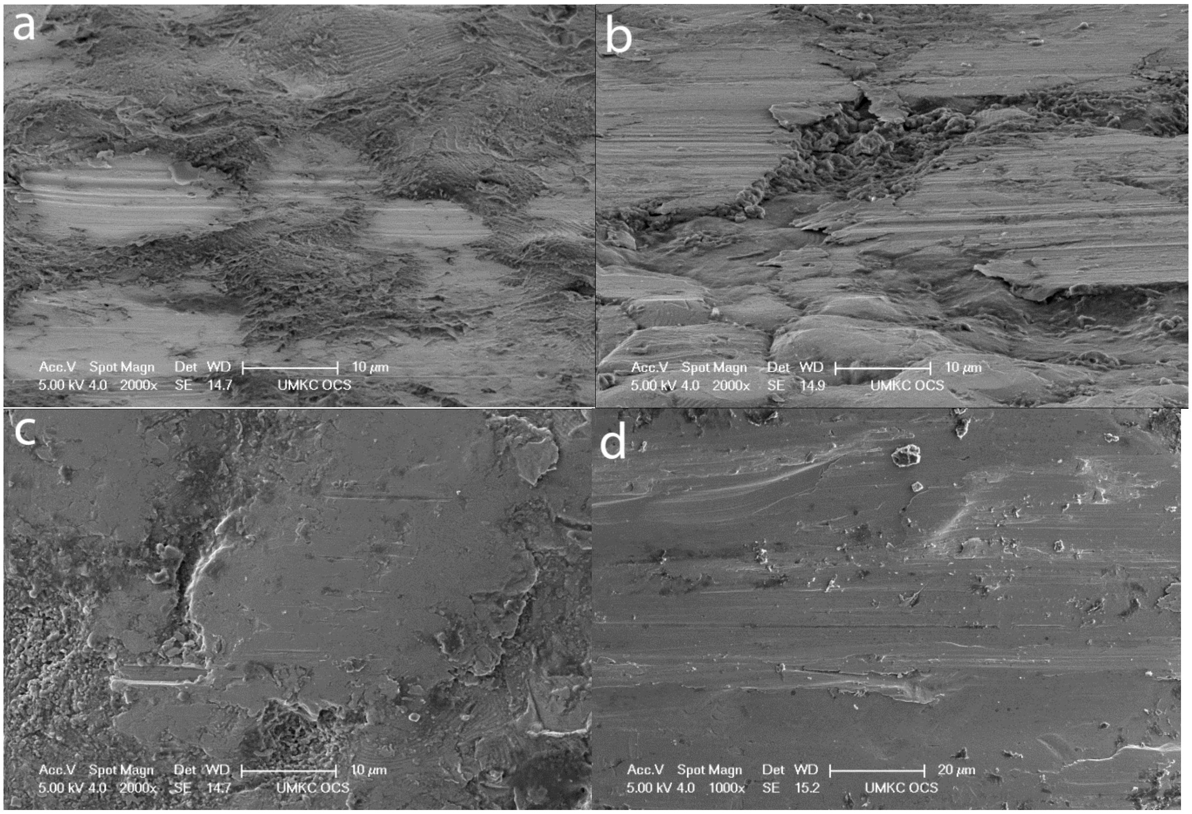

Figure 12. SEM images of striations in bracket slot. a) Striations found on a slot wall adjacent to the base of the slot in a new bracket following friction testing. b) Similar location as 'a', in a used bracket. c) Striations located on the raised mesial/distal ledge of the base of the slot in a new bracket. d) Similar location as 'c', on a used bracket

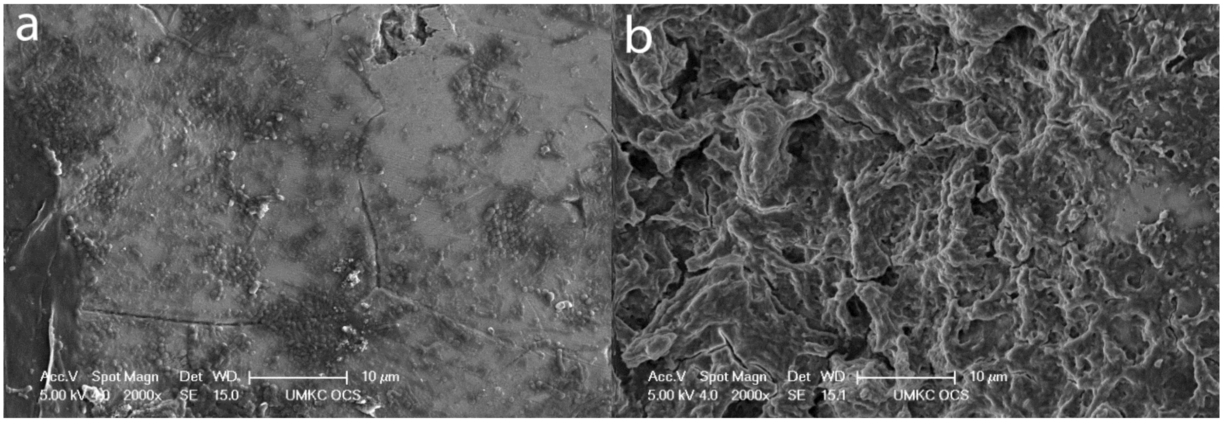

Figure 13. SEM Images of Granulation and Pitting Corrosion. a) Intergranular stress corrosion and b) pitting corrosion in a used bracket.

CHAPTER 4

DISCUSSION

Orthodontic stainless steel brackets remain in the mouth for approximately two years in the harsh oral environment. The stainless steel surfaces undergo corrosion which can affect frictional forces. This study focused on friction between an orthodontic bracket slot and archwire. Although many studies have been done to test friction of the wire sliding in the bracket slot, to date, none have tested a clinically used bracket and archwire that have remained in the oral cavity through complete orthodontic treatment. In this investigation, the used bracket and used archwire combination was tested and compared to a used bracket and new wire. A new bracket and new wire combination was also tested as a baseline where friction could be evaluated in the absence of corrosion.

Although the focus of this project was the consequence of corrosion on friction, a number of other factors influence the movement of the archwire in the bracket slot such as bracket material, method of ligation, archwire material, archwire diameter, archwire stiffness, wear of the archwire, active torque, surface roughness, sliding velocity, and bracket width and interbracket distance (Khambay et al. 2004). When debris produced by wear or corrosion products is present, it acts as a third body at the bracket/archwire interface and can alter the initial friction contact conditions (Al-Khatib et al. 2005). According to Al-Khatib et al., aqueous solutions act as a lubricant, lowering frictional coefficients compared to friction tests performed in ambient air (Al-Khatib et al. 2005).

Sliding mechanics are controlled by classical friction when the archwire sits in the bracket slot below a critical contact angle (Kusy and Whitley 1999). Once that angle is exceeded, binding and notching manifestations increasingly restrict sliding mechanics (Kusy and

Whitley 1999). Kusy et al. calculated the critical contact angle as the boundary between classical friction behavior and binding. Binding forces perpendicular to the sliding surfaces are introduced due to the mechanical couple generated at the edges of the bracket. The critical contact angle was found to be, theoretically, 3.7 degrees (Kusy and Whitley 1999). This means that the practitioner must level and align so that the angulation between the archwire and bracket slot is within 3.7 degrees or else binding will increasingly occur until sliding ceases altogether (Kusy and Whitley 1999).

Although care was taken in this study to ensure that a contact angle was not introduced during friction testing, large spikes in frictional force were registered and recorded. The second largest spike in forces came from a new bracket and new wire combination (NBNW_12). Because the bracket and archwire in the NBNW_12 had not been used in orthodontic treatment, the spike in frictional force cannot be attributed to notching of the wire from intraoral use of the materials. Instead, the possibility of notching from the manufacturing process or perhaps the accidental introduction of a contact angle/binding must be considered.

Most friction studies have focused on the effect of different ligation methods, wire materials, and bracket manufacturers on frictional forces. Thus, there are few studies comparable to the current study that show the effect of corrosion on friction of orthodontic brackets and archwires. One of these studies did demonstrate statistically significant differences in static and kinetic frictional forces after corroding different wire materials, one of which was stainless steel, in either 0.2% APF or pH 6.75 artificial saliva (Kao et al. 2006). Another study conducted by Ribeiro et al. collected clinically used premolar brackets which had been corroded in the mouth after an average of 30.7 months of orthodontic treatment (Ribeiro et al. 2012). Although Ribeiro et al. tested friction using brand new wires, and frictional values were collected at only two points during sliding, the corroded brackets showed higher frictional resistance than the non-corroded brackets (Ribeiro et al. 2012). Furthermore, a faster rate of 3 mm/min was used to draw the wire through the slot which could lower the value of larger spikes in the data, thus reducing overall frictional force averages. Interestingly, a Spearman analysis showed a strong correlation between frictional resistance and food debris and biofilm level variables, yet surface topography showed little association with frictional resistance (Ribeiro et al. 2012). Another study concluded that a clear relationship between surface roughness and the coefficients of friction does not always exist when adhesive or abrasive mechanisms are present (Kusy and Whitley 1990). When plotting the kinetic coefficients of friction against the surface roughness of the archwires, it can be seen that the kinetic coefficients are not systematically dependent on the surface roughness of archwires (Kusy and Whitley 1990). It is clear that friction between a bracket slot and an archwire is a complex system influenced by a multitude of factors. However, it is important for the practitioner to have an understanding of this system and the factors affecting it in order to successfully slide teeth into the desired position using currently available orthodontic materials.

Frictional force values reported in previous studies vary greatly depending on the setup used for friction testing. While the average of the overall means of frictional force values generated from this study was 0.0065 N, or 0.65 cN, it is important to remember that this was friction caused by a single, passively ligated bracket with no moment introduced. When Tecco et al. tested friction from pulling new wires through ten new brackets aligned in a row, frictional forces of 1620 – 2097 cN were reported when all ten brackets were ligated (Tecco et al. 2011). When only the terminal bracket was ligated, frictional forces were reduced to 151.4 – 251 cN. These values are approximately 200 – 3000 times higher than the values generated from the current study. Typically, in a clinical setting, more than a single tooth will be involved in the orthodontic mechanics and more than likely, there will be moments introduced. Therefore, 0.0065 N is the lowest amount of friction a clinician could expect to encounter. In another study, in which a ball bearing pedestal allowed for the bracket to tip to the limits permitted by the width and slot size of the bracket, frictional forces were quantified at 128 – 193 cN (Kapila et al. 1990). Although Kapila et al. used a single-bracket setup, tipping of the bracket was allowed introducing a moment and the resultant frictional forces were again 200 times larger than the values from the current study. Other factors that could affect the frictional forces in Kapila et al.'s study was the use of twin brackets ligated with elastic ties. Higher frictional values were seen using a dental typodont model in a study done by Henao and Kusy (2004). Pretreatment typodont models were replicated from a patient's oral cavity, brackets were bonded and friction was tested for each quadrant with a crosshead speed of 0.5mm/min. Due to the malocclusion, friction had to be tested with nickel-titanium (NiTi) wires. For 0.019x0.025 inch NiTi wires, maximum drawing forces averaged 1635 and 2080 cN for self-ligating and conventional brackets respectively (Henao and Kusy 2004). This setup represents the initial stages of treatment in which NiTi wires are used and the malocclusion introduces numerous moments causing higher friction.

SEM images did not show an association with surface characteristics and the amount of frictional force generated. This finding is consistent with a study by Ribeiro et al. (2012) in which friction was tested with new wires, and SEM imaging was used to look at debris on clinically used bracket and then surface corrosion after removing debris. Little association was found between surface topography and frictional resistance, however, a strong correlation was noted between frictional resistance and food debris (Ribeiro et al. 2012). Marques et al. (2010)

tested friction using new brackets and clinically used archwires which had been in the oral cavity for eight weeks. SEM imaging was done before and after exposure to the oral cavity and both debris and roughness were measured (Marques et al. 2010). After exposure to the oral environment, there was a significant increase in frictional force with an average increase of 1.48 N which corresponds to a 20.8% increase in the friction level. There was a significant association between friction and degree of debris as well as friction and roughness, but a greater degree of correlation was observed in the association between roughness and debris (Marques et al. 2010). Although Marques et al. did find a correlation with roughness and friction, both Ribeiro et al. and Marques et al. found that debris plays a major role in affecting frictional forces. Furthermore, if moments were introduced, or if a larger wire was used to fill the bracket slot further, it is possible that an association between surface corrosion and friction could be seen.

Study Limitations

The current in vitro study focused on surface roughness and its effect of friction. Many studies have been done to understand better friction in orthodontic materials, and none are without limitations. Attempts in past studies were made to replicate the oral cavity, however the oral cavity represents a dynamic and constantly changing environment with fluctuations in pH and temperature. Although friction testing was done in a temperature similar to the oral cavity temperature, and the stainless steel materials used in this study were corroded in oral cavities instead of with artificial saliva or fluoride, it is impossible to account for all variables that affect the environment in the oral cavity.

Friction is affected by a number of factors such as binding, debris, corrosion, notching of the archwire, and mechanical vibration. This study attempted to focus on the corrosion factor exclusively; however, it may be impossible to eliminate the other factors entirely. Care was taken to mount the bracket slots parallel to the archwire, but because of human error, precision could not have been perfect.

Because this was a pilot study, a convenience sample size of n = 10 was chosen for each of the three groups. A power analysis indicated that statistically significant differences could be detected at $n \geq 120$. However, based on the partial eta squared effect size test, which is independent of sample size, friction accounts for 2.5-3% of the variance seen and is not likely to be of any consequence if the sample numbers were increased.

In addition, although a cleaning process was performed to knock debris loose from the bracket slots, SEM imaging showed us that debris remained in the bracket slots. It may not be possible to remove all debris from the bracket slots without wiping the inside of the slot which could leave more dust or scratches.

Clinical Significance

The focus of this study was to examine the effects of intraoral corrosion of orthodontic brackets and archwires on friction between the archwire and bracket slot. The results imply that corrosion does affect friction, increasing static friction from 0.0138±0.0045 N in new brackets and new wires to 0.0174±0.0149 N in used bracket and used wires. Although the outcomes were not statistically significant, the trend in the data for static friction suggests that corrosion increases friction between the bracket/wire interface. The results from this study imply further that although corrosion is a factor increasing friction between the stainless steel orthodontic bracket slot and archwire, clinically, it does not increase friction so far as to warrant recommendation of changing brackets or archwires simply to eliminate corrosion. The raw data from UBUW_1 shows a large spike in frictional forces which were attributed to binding of the archwire within the bracket slot. However, if a practitioner is seeing less than expected tooth movement, friction and/or binding and its associated factors are something to consider.

When frictional force values seen during moments of binding or notching are applied to clinical situations, it is clear that these moments are capable of inhibiting tooth movement when forces from adjunct orthodontic apparatus such as elastics or springs, cannot overcome them. Often times, practitioners utilize interarch elastic wear to assist in space closure and/or tooth retraction and protraction. According to Wang et al., in vitro force degradation of orthodontic latex elastics was greatest in the first half hour of elastics wear (Wang et al. 2007). With interarch class II or class III elastic wear, force was at 80% of its original force after only 30 minutes of wear and by 24 hours, forces measured at only 65-73% of its original force (Wang et al. 2007). In non-latex elastics tested in vitro, average percentages of initial force were 49% at 24 hours (Kersey et al. 2003). Elastic force recommendations made by orthodontists vary, however most recommendations average at 277 ± 89 cN for class II correction and 290 ± 83 cN for class III correction (Oesterle et al. 2012). In the 4th edition of their book, Proffit et al. listed ideal interarch elastics forces used with rectangular wires of relatively large cross-section to be 250 g per side (2007b, 591-592). Although the elastic forces suggested in this textbook are not substantiated by experimental data, they are in fact lower than the values reported in the studies above which would make the following scenario even worse. If the practitioner instructs a patient to wear class II elastics and the elastic force starts out at 277 cN, after 24 hours it can be expected that the force decays to about 180 cN (65% of 277), which is below peak measured frictional forces of 200 cN calculated from the 0.2 N spike and gravitational constant.

Future Research

Because this study focused on the effects of intraoral corrosion of orthodontic brackets and archwires on friction between the archwire and bracket slot, no mechanical moments were introduced at the bracket-wire interface. Clinically, much more than surface friction is involved in sliding mechanics. There is often binding of the archwire in the slot from contact angles formed due to the archwire not sitting perfectly parallel in the slot or from notching of the archwire that can get caught on the edge of the bracket slot. Kusy et al. (1999) described binding as the introduction of contact angles by the rotation of the bracket so that the wire sits at an angle within the bracket slot. However, the focus on geometric orientation is less informative than the calculation of mechanical couples produced by the application of load at a particular distance from the center of resistance. It is the couple that is the independent variable that must be measured. The magnitude of the couple is determined by several factors such as size of the wire cross-section, width of the bracket slot, wire material, and wire deflection. Hence an improved in vitro experimental testing apparatus should address these factors. More specifically, an improved apparatus that facilitates prescribed incremental changes in couple-related forces at the bracket-wire interface thus controlling increases in the normal forces on the wire and making it possible to demonstrate the effects mechanical moments have on frictional forces (fig 14). With such a system, a controlled rotation can be applied to the bracket introducing a contact angle. Thus, when using a corroded or clinically used archwire to pull through the bracket slot, the amount of force needed to overcome general surface friction associated with that moment could be quantified. Furthermore, the amount of force needed to overcome a notch in the archwire catching the edge of the bracket could also be quantified. By creating mechanical moments beyond basic surface friction and observing the magnitude of force needed to overcome them, clinicians could get a better idea of the limitations of sliding mechanics. In scenarios where tooth movement is halted by binding or notching of the bracket/archwire system, clinical implications would cause the clinician to change to a new archwire or bracket in order to resume tooth movement.

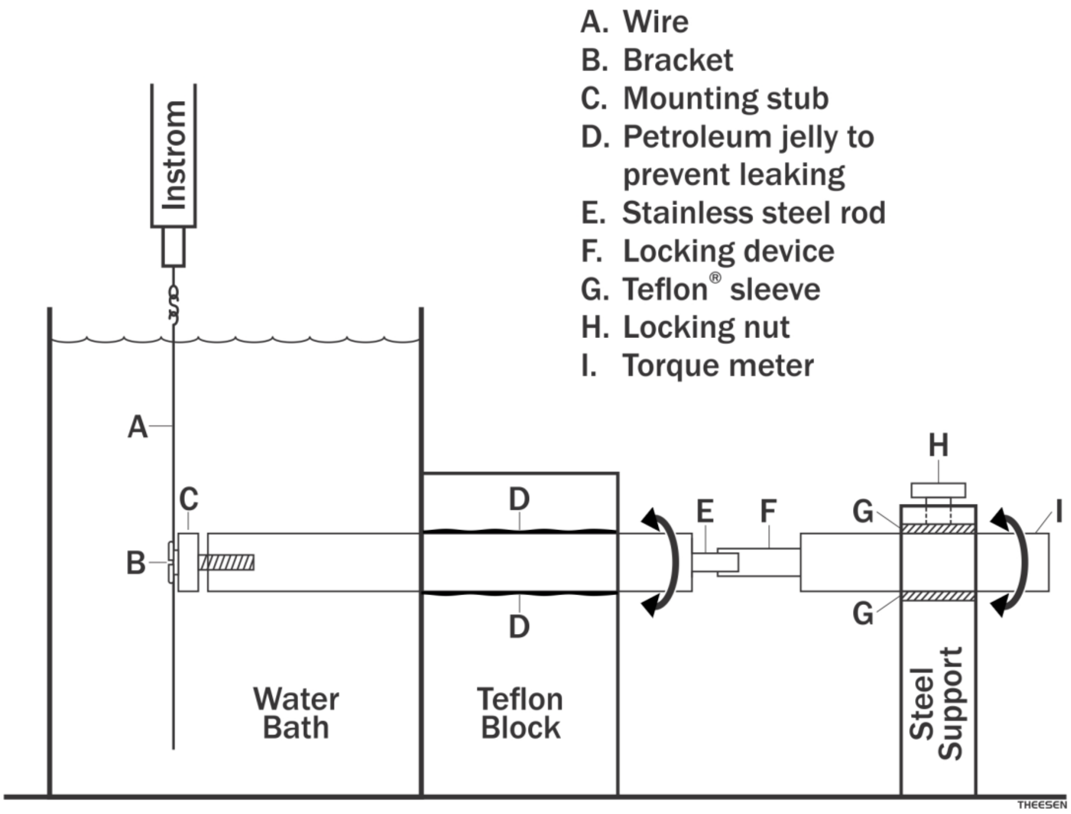

Figure 14. Diagram of future project introducing moments

CHAPTER 5

CONCLUSIONS

1. There were no significant differences in frictional force of the bracket/wire system with exposure to the oral environment.

2. There was a qualitative difference in surface topography of brackets and wires as a function of exposure to the oral environment.

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INTERNSHIP AND/OR RESIDENCIES:

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PROFESSIONAL ORGANIZATIONS:

American Association of Orthodontist
American Dental Association
American Student Dental Association
American Dental Education Association
American Dental Political Action Committee
International Association of Dental Research

HONORS:

High Academic Achievement & Graduating with Honors. UNMC College of Dentistry (2012)
Chi-Cheung Chan Orthodontic Award. UNMC College of Dentistry (2012)
UNMC College of Dentistry Dean’s Honor List (2009-2011)
Wy-Dent Recipient. State of Wyoming (2008-2012)
Summer Student Research Fellowship Award (2010)
MESNA Education and Research Foundation—Grosswirth-Salny Scholarhip (2010)
Trona Valley Federal Credit Union Scholarship (2009)
University of Wyoming Gold Award (2007)
County Commissioners Scholarship (2004-2007)
University of Wyoming President’s List (2004-2007)

PUBLICATIONS:

L. Petersen, J. Shin, T. Premaraj and S. Premaraj, PGE2 mediates mechanical strain-induced up-regulation of Cx43 in PDL cells, J. Dent Res, 90 (Spec. Iss. A) 3646, 2011