Effect of Mechanical Vibration on Resistance to Sliding in the Fixed Orthodontic Appliance

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EFFECT OF MECHANICAL VIBRATION ON RESISTANCE TO SLIDING IN THE FIXED ORTHODONTIC APPLIANCE

by

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ABSTRACT

EFFECT OF MECHANICAL VIBRATION ON RESISTANCE TO SLIDING IN THE FIXED ORTHODONTIC APPLIANCE

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Objective: To determine the effects of mechanical vibrations produced from electric tooth brushes and a commercially available device called AcceleDent, on the resistance to sliding at the bracket-arch wire interface.

Materials and Methods: All as-received wires and brackets were cleaned with 95% ethanol prior to testing. An individual metal bracket was mounted on a custom metal fixture. The custom metal fixture had a polyurethane material that resembled the mechanical feature of the human periodontal ligament. The test metal bracket was aligned and bonded passively with 4 other non-movable brackets using a straight piece of .0215” X .025” SS wire. Another test bracket was then bonded at a 2 mm offset from the other test bracket. A new wire (7 cm straight piece of .016” X .022” NiTi) was ligated to the brackets using a conventional ligature tie. Resistance to sliding was measured over a 7 mm sliding distance using the mini-Instron universal testing machine with a 50 Newton load cell and a crosshead speed of 5 mm/min. Initial control testing of static and kinetic friction were performed. After baseline tests (control) were established, mechanical vibration was introduced to the testing both with electric tooth brushes and an AcceleDent device. During each test run, new test brackets and test wire were used and bonded in the same fashion as stated above. The effects of mechanical vibration on the static and kinetic friction were recorded and analyzed using one-way ANOVA with Tukey *Post Hoc* comparison. Statistical significance was considered when p value was less than 0.05.

Results: Compared to the control (no vibration), the AcceleDent static and dynamic resistances to sliding were reduced by 8.5 % and 22.26 %, respectively. The Oral B side test group showed reductions of 14.6 % and 22.46 %. The Sonicare side test group showed reductions of 11.46% and 28.51%. The Oral B front test group showed reductions of 12.73 % and 30.3 %. The Sonicare front test group showed reductions 11.18 % and 28.84 %. All these changes were statistically significant ($p = 0.000$), with no significant differences found between vibration sources.

Conclusions: Mechanical vibration from AcceleDent and electric tooth brushes significantly reduce the resistance to sliding in the orthodontic bracket-wire interface.

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CHAPTER 1
INTRODUCTION

Over the past few decades, there has been much debate over the role that friction has on the ability to effectively move teeth along an arch-wire (1). Variations in the type of bracket or arch-wire used can change the amount of friction present at the bracket-arch-wire interface (2). In addition to the different arch-wire materials and bracket types changing the frictional resistance, vibration of arch-wires from forces of mastication has also been implicated in changing frictional forces at the bracket interface (3). More recently, other forms of vibration have been introduced; the increasingly widespread use of electric tooth brushes and the emergence of new products that introduce mechanical vibration (such as AcceleDent) have exposed the current orthodontic patient population to a new variable that could potentially have an effect on friction and tooth movement. The additive effect that mechanical vibration and the innate forms of vibration that occur intra-orally are unknown.

Friction plays a role in almost all orthodontic treatment movements and occurs whenever there is relative movement between arch wires and brackets. There has always been an emphasis on the magnitude of friction present in the fixed appliance system because friction is considered to be significant in decreasing the effective orthodontic force needed to move teeth; which will reduce the efficiency of tooth movement and thus increase the treatment time (4). Friction can be defined as a resistance to the direction of movement on two contacting surfaces. Even two relatively smooth surfaces will produce a frictional force when they are pressed together due to surface irregularities on each material called asperities (Fig. 1). The asperities create junctions that contact each other and will eventually shear once there is a force placed against the two materials (5).

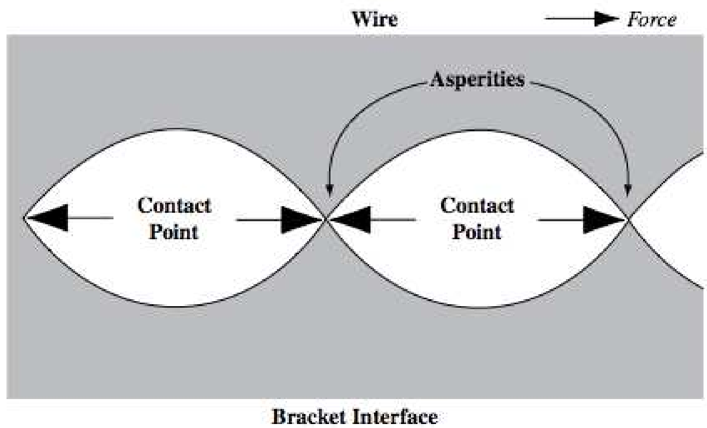


Figure 1. Magnified schematic view of two surfaces sliding against each other. Contact between the two surfaces occurs only at the microscopic peaks called asperities (5).

When friction is analyzed in the fixed appliance system, there is more of a “stick-slip” behavior that takes place intra-orally. Due to the low sliding speeds of the wires against the bracket slot, the wire will occasionally get “stuck” until enough force is produced to break the junctions between asperities of the two surfaces (5).

Friction can be divided into two main types that are significant for orthodontic movement. Static friction is the type of friction that is first encountered when two opposing surfaces touch one another; it can be defined as the amount of force required to start movement of the wire against the bracket slot. Kinetic friction can be measured once the wire starts to move against the bracket slot. The force required to keep the wire moving along the bracket slot is the kinetic friction (6).

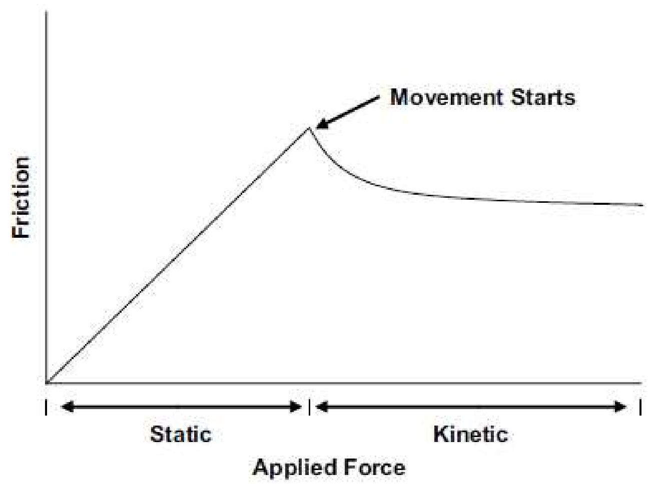


Figure 2. This graph depicts the change from static friction to kinetic friction. Movement does not start until enough force builds up to overcome the initial resistance (6).

Figure 2 illustrates the differences between static and kinetic friction. Static friction can be thought of as the “startup” force required for tooth movement, while kinetic friction is the force it takes to keep that movement going. Both static friction and kinetic friction can be measured effectively in a laboratory setting because the force applied to an experimental set up is constant. However, it is very difficult to apply the concept of kinetic friction to a clinical situation because continuous movement of an arch-wire never occurs intra-orally (6).

Although friction is one of the fundamental components of resistance to tooth movement, Kusy and Whitley describe additional components that classify the different aspects of resistance to movement at the bracket-arch wire interface. When clinicians mention “friction”, they are really discussing three different phenomenon. These include friction, binding, and notching. The frictional component is the resistance to movement between the two surfaces. This “classic” type of friction can either be static or kinetic and usually contributes to a small portion of the overall resistance to movement (7). The more important concept and the one that contributes the most to inhibiting tooth movement is the concept of binding. Binding of an arch-wire occurs when contact takes place between the wire and corner of the bracket. An example of binding can be found during the leveling and aligning stage of orthodontics, where the wire (usually NiTi wire) will bind with the edge of the bracket (Fig. 3). The binding will contribute to the resistance to sliding movement; binding of an arch-wire will eventually release as the force on the wire increases. The binding and then the subsequent release of the binding through small arch-wire or tooth movements is part of the "stick-slip" phenomenon discussed above.

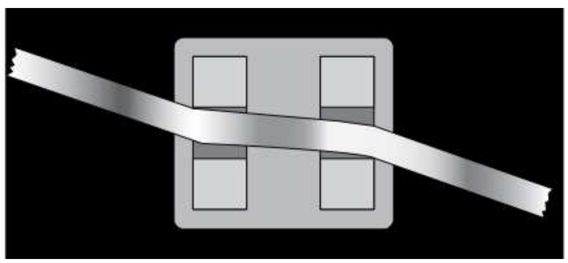


Figure 3. Binding of the arch-wire against the corner of a bracket slot that occurs with leveling or repositioning or brackets. Notching of the arch-wire will occur if this leads to permanent deformation of the wire (6).

The third concept that contributes to the overall resistance to sliding is notching. Notching occurs when the wire becomes permanently deformed at the corner of the bracket and wire interface. This prevents movement of the wire through the bracket slot. The threshold at which the wire changes from plastic deformation to permanent deformation represents the change from binding to notching of the arch-wire (5).

With the evolution of the "friction" concept introduced to orthodontics, the binding and notching phenomenon were added to the classic frictional model to coin the term "resistance to sliding." Kusy and Whitley introduced the formula: RS = FR + BI + NO, which states that resistance to sliding of an arch-wire is equal to the sum of its frictional resistance added to binding and notching forces (7). Resistance to sliding encompasses a frictional component, along with biomechanical dynamics, the binding of the arch-wire to the bracket complex, and the release of that binding by tooth movement and other motion within the system (8). The contact angle that the wire forms with the bracket determines whether the resistance to sliding is comprised of purely a frictional component or a binding component. For example, during space closure with a rectangular stainless steel wire, the brackets are already aligned and sliding mechanics are used to close spaces. Most of the resistance to sliding occurs in the form of friction due to the full size arch-wire contacting the bracket slot. This situation is different during leveling or repositioning of brackets, where the contact angle between the bracket and arch-wire has increased. In this scenario, most of the resistance to sliding occurs due to the binding of the arch-wire (Fig. 3). Articolo *et al*. confirmed that as contact angle increases past 3° binding will contribute more to the overall sliding resistance when compared to classic friction (7).

CHAPTER 2
LITERATURE REVIEW

Over the last 40 years, there have been over 70 articles that have been related to bracket/arch-wire friction (9). Variables such as ligation method, arch-wire type, and test environment e.g. fluid media have all been studied for their various effects on friction and resistance to sliding. Most laboratory studies that use conventional brackets must consider which ligation method to use: they are generally ligated with elastomeric ties due to the operator variation found with steel tie ligation (10). Although less friction is produced with steel ligature ties, the variation between operators that tie each ligature causes some to be tighter than others, which can greatly affect the friction (11). The length of time it takes to ligate a test wire into the brackets with stainless steel ligatures is also a drawback to their use; which is another reason that conventional elastomeric ties are used for friction testing.

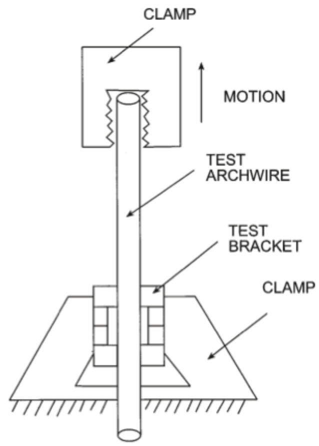
Another potential testing variable that can be added when testing conventional brackets is whether or not to include fluid media in the testing. Decay of elastomeric modules usually occurs after being in the intra-oral environment for approximately 4 weeks (12). Conventional brackets have been tested in both dry and wet states with artificial or real saliva. Keeping the testing conditions dry would eliminate the potential for variation and errors in the amount of solution applied to the brackets. However if testing in a wet environment, only human saliva should be used to assess friction and its coefficients (13).

When comparing conventional brackets to self-ligating brackets, the self-ligating brackets produce less frictional resistance during bench-top testing (2, 11, 14). Passive self-ligating brackets provided the largest reduction in sliding resistance compared to active self-ligating brackets (2). This is most likely due to the active portion of the clip adding another layer of material and increasing the frictional resistance in the active ligating brackets. Variations in the type of arch-wire used for testing will also affect the sliding resistance. Of the three most popular types of arch-wires used today, TMA increases the resistance to sliding the most, followed by nitinol, and then stainless steel wires which have the least amount of frictional resistance (2, 15, 16).

Despite the numerous studies on variables that affect resistance to sliding, very few studies have investigated the effect of vibration on the fixed orthodontic appliance. Vibration can be introduced in a number of ways to the bracket/arch-wire system, either by various oral functions such as chewing, swallowing, and speaking (17) or by an external vibration source such as an electric tooth brush or AcceleDent device. Hixon *et al*. completed one of the first studies testing arch-wire vibration on frictional resistance in 1970. They used an electric vibrator (60 Hz) and tested its effect on kinetic friction both *in-vitro* and *ex-vivo* (18). Once vibration was introduced into the system, they found that kinetic friction was essentially eliminated and deemed it to be insignificant.

In 1991, Brinkman and Miethke completed another study evaluating tooth mobility and frictional resistance. Similar to the Hixon study, they used two different experimental set ups, one being in the laboratory and the other being intra-orally on volunteer test patients. After the test tooth was loaded with a force, they found that there was a significant reduction in the friction. This test concluded that forces from mastication caused a reduction in the friction. They also concluded that frictional forces are measured to be much less intra-orally than an *in-vitro* experiment using an immovable bracket (19). Further testing by Liew *et al* used low frequency vibration (91.3 cycles/min) to replicate masticatory function. In this *in-vitro* study, the vibration caused repeated vertical displacement of the wire, which caused a reduction of friction by 85%. Liew *et al*. concluded that friction between arch-wires and brackets is not an important factor for orthodontic tooth movement unless tight ligatures or moderate/severe angulation of the arch-wire/bracket slot inhibits movement (4).

More recent studies over the past 15 years have also looked at various forms of vibration and their effect on friction. *Braun et al*. applied perturbations to an arch-wire in conjunction with a universal testing machine (Instron) (17). Perturbations consisted of applying finger pressure to the bracket or arch-wire. This study and Liew's study were the first to incorporate perturbations or disturbances in a way that mimics chewing and/or swallowing forces. Stainless steel brackets were tested using both rectangular and round stainless steel wire. Random perturbations were applied to the bracket or arch-wire at random times and frequencies during the testing. This study was unique because it migrated away from the traditional lab set up used in previous friction studies (Fig. 4). Instead of the wire being drawn through an immovable test bracket, brackets were mounted on a jig that allowed for different bracket angulations between 0° to 25.5°.



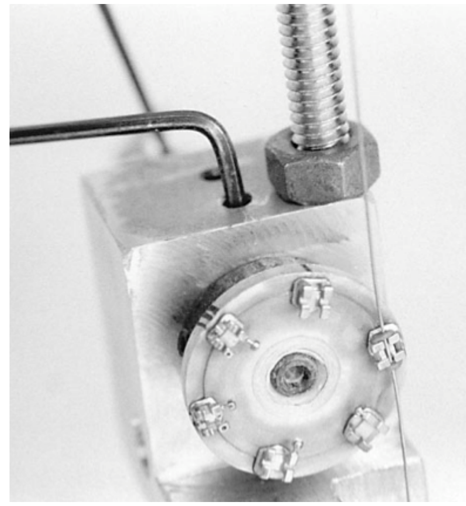


Figure 4. Left – This shows a traditional way to test frictional forces, where an arch-wire was drawn through an immovable test bracket. Right – Braun's testing setup included a Jig that allows for changes in bracket angulation (17).

This change helped to simulate tipping movements that occur intra-orally. Braun *et al*. concluded that each perturbation caused a significant reduction in the amount of friction, regardless of the type of wire or ligation method used (17). It was also found that relative bracket/arch-wire angulations of up to 25.5° do not increase the frictional resistance once perturbations are applied to the system. This implies that perturbations were able to release the binding and notching that occurred at the bracket-wire interface when the critical angle was exceeded.

O'Reilly *et al*. used a vibrating machine (LDS Oscillator®, Model D207) to test the amount of tooth movement required to release binding at the bracket arch-wire interface. Test brackets were mounted onto a plastic sheet and the test set-up included a two-part swivel mechanism (Fig. 5). This allowed for rotation of the test bracket relative to the immovable test brackets; thus mimicking physiologic movement consistent with clinical practice (9). This experimental set up differed from Braun's because O'Reilly *et* *al.* eliminated the cantilever from the design by including a bracket below the testing bracket; studies that have the test bracket on the free end of the set up are not emulating a true clinical situation.

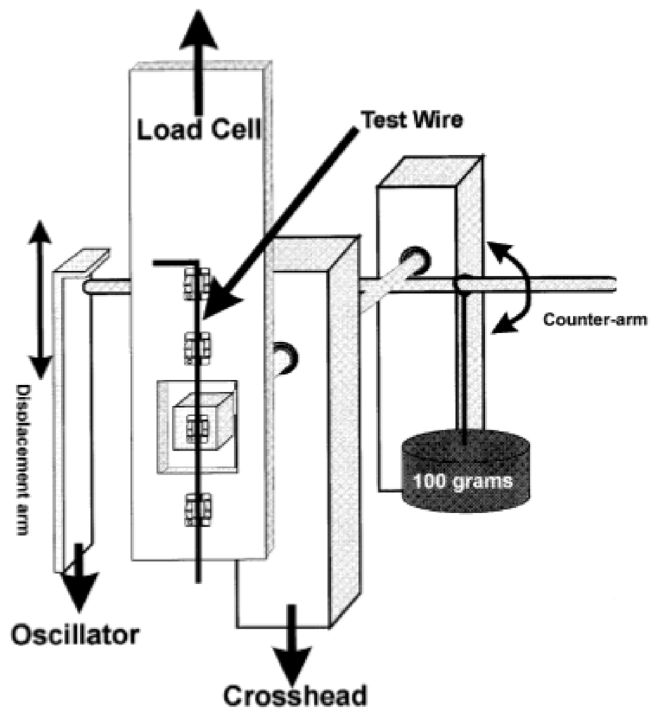


Figure 5. Testing set up that included a vibrational source (oscillator) and two separate mounting plates allowing for bracket movement (9).

Using this testing set up, O'Reilly found that the amount of displacement or "vibration" from the oscillating machine had a direct relationship with the release of binding; the greater the displacement, the faster the binding was released from the test bracket. This study also tested different types of arch-wires, finding that the largest reduction in resistance to sliding came from the rectangular stainless steel wires, which are generally the wires that are used in with sliding mechanics. O'Reilly concluded that sliding resistance can be effectively reduced by repeated displacement of an arch-wire equivalent to .16mm crown movement. This study also implies that this repeated displacement could potentially come from normal forces of mastication and that the influence of friction alone is small and relatively insignificant. In the conclusions of this study, more emphasis is placed on the binding and release phenomenon, which is more important for tooth movement than reduction of the classic frictional forces (9, 12).

After Braun and O'Reilly incorporated bracket angulation into their studies, Kusy and Thorstenson looked at self-ligating brackets and the effect that second order angulation had on binding of arch-wires. It has previously been shown from the above studies that vibration or perturbations will release binding and reduce friction on the test bracket. Thorstenson and Kusy used four different self-ligating brackets and a combination of arch-wires to test the effect of wire clearance within the bracket slot. They found that when clearance between the bracket and arch-wire slot no longer existed, there were both a frictional component of the wire against the clip, and a binding component. Once the second order angulation increases beyond a critical angle, the resistance to sliding increased proportionately. Furthermore, the rate of binding was independent of bracket design. These revelations were important to friction studies because it stressed the importance of testing the binding component of resistance to sliding (20).

From three of the previous bench-top studies mentioned above (4, 17, 18), it can be concluded that friction is essentially eliminated from the bracket interface when vibration is introduced to the system. Vibration was introduced either in the form of finger pressure or vibration machines that were supposed to replicate intra-oral forces. In

2003, *Iwasaki et al*. completed an intra-oral study where subjects chewed gum for 3-5 minutes at a vibration frequency of approximately 60 Hz, testing the effects of arch-wire deflection and vibration. The test subjects each had a bracket/moment spring assembly placed intra-orally and friction was measured with a friction-measuring device. After chewing gum for 3-5 minutes, force measurements were taken for a 1-minute period. They found that mastication alone did not significantly reduce frictional forces in the orthodontic appliance. *Iwasaki et al*. also suggested that normal forces produced by ligation (how tightly the arch-wire is ligated into the bracket slot) have a significant effect on frictional resistance (10). As stated in the article, it could be a possibility that the duration of chewing could be too short to obtain adequate and representable data. It was also proposed that more work could be needed to increase the amount of vibration at the bracket/arch-wire interface in order to overcome the initial static friction. Despite these potential limitations of the study, it does contradict the previous bench-top studies in regards to vibration/masticational forces completely eliminating the components of friction.

The effect that arch-wire vibration has on the binding and release phenomenon was further investigated by Olson *et al*. This group followed up on the above study (Iwasaki *et al*.) by completing a dual experiment composed of both *in-vivo* and *ex-vivo* testing. *In-vivo* testing involved calculating the frequency and amplitude of vibration placed on the orthodontic wire during carrot biting. Orthodontic patients were instructed to incise on raw carrots while an accelerometer was ligated to their maxillary canine bracket. This allowed for frequency and amplitude of the vibration to be measured intra-orally.

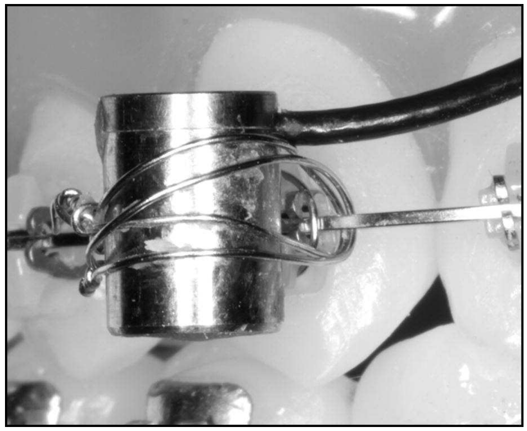


Figure 6. Piezo-resistive accelerometer ligated to Maxillary canine in the occlusal-gingival direction, which allows vibrational frequencies and amplitudes to be measured at the wire/bracket interface (3).

These measurements were then used in the bench-top portion of the study to test various amplitudes and frequencies in a more controlled setting. The bench-top vibration testing used a range of vibrational amplitudes and frequencies. Variation of amplitude/frequency levels during testing differs from previous studies (4, 10) that did not include these as dependent variables. Olson *et al.* found that frictional resistance was not significantly affected by the frequency of the vibration, but was reduced when medium or high amplitudes were used (3). Changing the amplitude of the vibration source essentially causes more vertical displacement of the arch-wire being tested, whereas altering the frequency will change how fast the wire is moving vertically in the bracket slot. Using a prediction analysis, Olson *et al*. also found that regardless of the bracket used (active vs. passive self-ligation), both types are predicted to perform best at extreme amplitudes of greater than 200 mV, which equals approximately .32 mm of vertical displacement (3). This finding is similar to earlier studies (9), which reported a correlation between vertical arch-wire displacement and a reduction in sliding resistance.

All of the above studies that have incorporated vibration have based their experimental design on the replication of intra-oral movements such as chewing and swallowing. Reproducing vibration *in-vivo* to mimic masticational forces has occurred with perturbations, oscillating machines, and other devices that cause displacement of the arch-wire in the bracket slot. With the availability of electric tooth brushes and AcceleDent (OrthoAccel Inc.) to the orthodontic patient, there has also been an introduction of a new form of mechanical vibration to the bracket arch-wire complex. Two of the most popular electric tooth brushes are the Oral B Precision 5000 (Braun Inc.) and Sonicare Diamond Clean (Phillips Inc.). Both of these tooth brushes deliver high frequency mechanical vibration to the bracket/arch-wire interface. In addition to orthodontic patients utilizing electric tooth brushes, another product called AcceleDent also introduces mechanical vibration in the form of a mouthpiece that the patient is required to bite on for approximately 20 minutes per day. There have been no studies that test these new forms of mechanical vibration and their effect on resistance to sliding in Orthodontics.

Whether the practitioner believes that resistance to sliding can be completely negated by normal mastication and everyday intra-oral vibration is debatable. Introducing mechanical vibration to the fixed appliance could help potentially decrease the frictional resistance and binding of the arch-wire/bracket interface even more than just relying on conventional mastication forces to release binding alone.

This study investigated the effects of mechanical vibration on clinically relevant scenarios involving alignment of teeth. Modifications to the standardized testing protocol were introduced to make testing more like clinical situations.

CHAPTER 3
MATERIALS AND METHODS

Most traditional *in-vivo* testing setups include an immovable test bracket and pull a straight piece of wire through this bracket using a universal testing machine. This study attempted to make improvements on these previous study designs. Certain materials and testing protocol were used from previous research studies completed in the Graduate Orthodontic Program at Marquette University (21). Straight pieces of NiTi arch-wire (.016" X .022", item # 857-641, American Orthodontics, Sheboygan, WI) were cut into 7 cm long pieces. This diameter wire was chosen for testing because it was the only NiTi wire that came manufactured in straight lengths (as opposed to testing with round NiTi). After cutting the wire, a 90° bend was placed at the end of the wire to act as a stop. Test brackets were .022" X .028" slot premolar brackets with zero degrees of tip and torque (item #380-0021, American Orthodontics). The arch-wires and brackets were cleaned with 95% ethanol and allowed to dry before testing began; this removed any residue left from the manufacturing process.

Two custom metal plates were obtained (21) and modified by incorporating a periodontal ligament replica in between the two plates, allowing for mimicking physiological movement of the test bracket. In order to properly modify the plate to replicate the periodontal ligament, various materials were tried; the material had to allow for movement of the plates, but also have some adhesive properties to allow the pieces of the plates to stay connected.

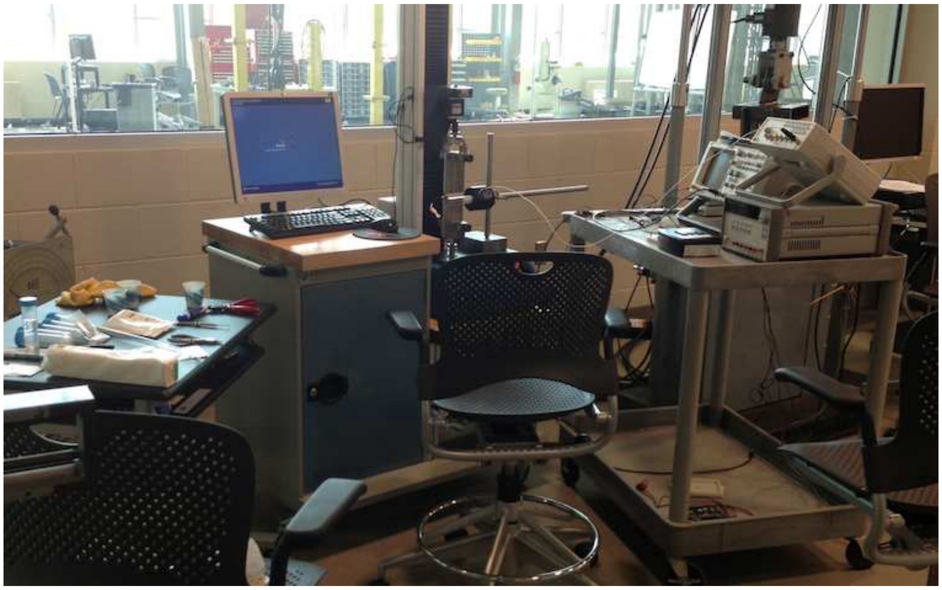


Figure 7. Photo of testing setup- Mini Instron machine and accessary

The test fixture was designed to approximate the natural frequency of the PDL. Dr. Philip Voglewede from the Marquette Engineering Department contributed to helping design this fixture and made the calculations below. Using a fundamental model of a material with a rectangular cross section, the stiffness can be found by:

$$k = \frac{AE}{L}$$

where *A* is the cross sectional area, *L* is its thickness, and *E* is its modulus of elasticity. The natural frequency of the moving piece can then be found by:

$$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{AE}{Lm}}$$

Where *m* is the mass. Unfortunately, the natural frequency of the PDL is not widely known. In fact, the modulus of elasticity has widely reported values. Thus, the natural frequency of a tooth was estimated by approximating it by using the equation above with parameters and an average modulus of elasticity. That is:

$$\omega_{nt} = \sqrt{\frac{AE}{Lm}} = 12,700\, rad\,/\,s$$
$$m_t = 1.2 grams$$
$$A_t = 34 mm^2$$
$$L_{PDL} = 250 \times 10^{-3} mm$$
$$E_{PDL} = 0.71 \times 10^6\ Pa$$

For the aluminum piece, the mass and cross sectional area is known. A polyurethane caulk with a low modulus was utilized and the thickness of the caulk, *L*, was modified to match the given natural frequency. For this particular application:

$$\omega_{nt} = \sqrt{\frac{AE}{Lm}} = 12,700\, rad\,/\,s$$
$$m_{Al} = 23 grams$$
$$A_{Al} = 456 mm^2$$
$$L_{poly} = 0.383 \times 10^{-3} mm$$
$$E_{poly} = 3.105 \times 10^6\ Pa$$

After assembling the lower plate by adding the correct thickness of caulk, grooves were cut into the plate in 1mm increments to allow for consistent bonding of test brackets to the lower fixture. The upper plate contained 4 brackets mounted in a groove. The upper testing plate essentially acts as one large bracket, as there is no movement between the 4 brackets during testing. These brackets insured proper alignment of the test brackets on the lower plate.

The upper and lower plates were mounted to the Universal testing machine (Mini-Instron, Canton, MA). The mini-Instron machine was equipped with a 50-Newton load cell and ran at a crosshead speed of 5 mm/min. To begin each test, the plates were positioned 10 mm apart. This distance is similar to the distance found between two brackets in the mouth (depending on which teeth and if space is being closed). Two test brackets were then positioned onto the lower plate. The first test bracket was positioned on the lower member of the lower plate by aligning it with a straight piece of .0215” X .025” SS wire so that it was positioned passively with the 4 brackets on the upper plate. The second test bracket was positioned in the center of the upper member of the lower plate, at a 2 mm offset to the other brackets, allowing for binding of the arch-wire once it was ligated into place. The 2 mm bracket offset was positioned by the vertical scribe lines cut into the plate. The test brackets were bonded to the plate using Transbond composite resin (3M Unitek) and light cured for 10 seconds (Blue Ray II Micro flash LED, American Orthodontics) each to ensure they would not de-bond during testing.

After mounting the two test brackets on the lower plate, the test wire could be ligated into the system. Conventional elastic ties (3M Unitek) were used to ligate the test wire to the bottom test bracket on the upper plate and then into the brackets on the lower plate. New elastic ties (3M Unitek) were used for each test; each was ligated in the same manner for each test and always performed by the same operator. The 90° bend placed at the terminal end of the test wire prevented any movement of the arch-wire once the Instron machine started pulling it vertically upward.

Figure 8. Photo of testing setup after test was run, illustrating bracket offset and terminal bend of wire. The upper plate had a groove with 4 brackets mounted to it. The lower modified plate was cut into two pieces. The white layer was the PDL replica that allows for physiological mobility of the upper test bracket**.**

The addition of the terminal bracket and the offset of the test bracket make this system non-passive. Before starting each test, the system was checked to make sure there was not a load/force being placed on the wire; the measured load was zeroed before each test. Upon starting the Instron machine, the wire was pulled vertically and the upper member with the attached wire moved vertically. The static friction value was recorded as the peak force needed to initiate the movement. Kinetic friction was measured after 5 mm of sliding; this value for kinetic friction (after 5 mm of testing) was arbitrarily picked because it adequately represented the dynamic force for each specific trial. Fifteen trials were run for each set of new testing conditions, using a new test wire and two new testing brackets each time. All brackets on the upper member remained in place, as they were only mounted to insure passive alignment of the lower test bracket. All tests were conducted under dry conditions, without adding any form of fluid media to the bracket-ligature interface.

Before adding mechanical vibration to the test set up, the pressure of the vibration source against the plate was calibrated. Using a bite force sensor (flexi-force sensor, Tekscan) and an intra-oral vibration device (AcceleDent), there was a pilot study completed to determine the optimal bite force value required to hold the device between the maxillary and mandibular dentition. The AcceleDent mouthpiece was modified so that the bite force sensor fit inside the plastic mouthpiece in the posterior region. Investigators DK and DL recorded bite force values 6 consecutive times at “relatively light pressure”, which are the instructions given to patients who use the device during orthodontic treatment. Trials were completed with the unit in the on and off positions, to see if there was any variation in bite force with the addition of vibration. It was found that there was a range of bite force values for each investigator, but that it reliably fell between 50-250 grams for each test. Each investigator had a relatively constant recording regardless of whether the device was vibrating or not. It was also shown that each investigator has a different idea of what is considered to be “light pressure,” which accounted for the larger range of pressures.

Once the bite force values were obtained through the pilot study, the values were replicated on the testing plates with the help of the bite force sensor. The bite force sensor was secured to the side of the lower test plate (Fig. 9), allowing for mechanical vibration to be delivered to the test bracket and PDL replica portion of the plate. Each source of mechanical vibration was calibrated with the bite force sensor. For the AcceleDent unit, the mouthpiece was pressed against the sensor and side of the lower plate. Amount of deflection of the plastic mouthpiece needed to produce force values between 50 and 250 grams was observed. For the electric tooth brushes, the amount of deflection of the bristles was used as a measure for replication of correct tooth brushing technique. These deflection points were then used during testing to replicate an intra-oral situation and to deliver acceptable force levels over the range found from the pilot study.

Figure 9. Bite force sensor and AcceleDent unit

After control testing was completed with the two test brackets and rectangular NiTi wire, mechanical vibration was added and 15 trials were run for each source. The brackets were mounted onto the lower plate in the same process as described above. The mechanical vibration devices were mounted with clamps to a steel rod connected to a large rectangular steel base, which kept the unit stationary during and between each trial. This allowed the deflection of the device to remain consistent throughout the 15 tests. After the device was secured to the clamps, it was positioned to touch the side of the lower plate with the similar deflection needed to achieve an acceptable force level to mimic biting force or tooth brushing forces. Each device was turned on just before the Instron machine was started, allowing any effects of the vibration to be reflected immediately in the static frictional coefficient. The vibration was constant while the wire was pulled over the 7 mm sliding distance, again allowing any potential effects of vibration to be shown with the kinetic friction value. Once each test was complete, the vibration source was turned off while new test brackets and wires were placed.

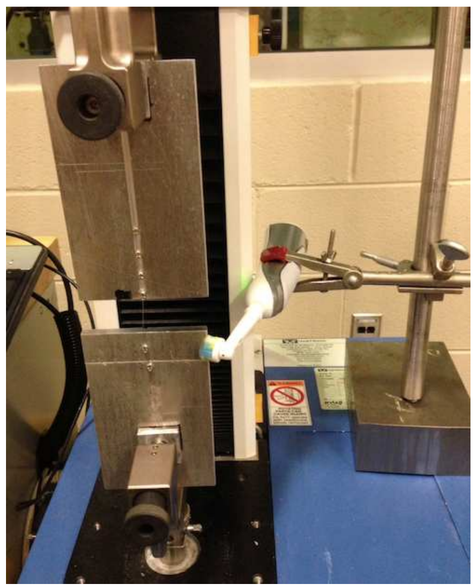


Figure 10. Mounting Clamp attached to steel base. All three testing devices were mounted in this way.

Each mechanical vibration device was tested from the side of the lower plate, which mimics the vibration being applied in direct contact with the teeth intra-orally. This clinical situation holds true for the AcceleDent mouthpiece, which touches only the teeth. However, the electric tooth brushes also come into contact with the bracket and arch-wires during usage. This clinical situation was tested by positioning the mounted tooth brushes directly against the upper test bracket while the Instron machine was pulling the wire vertically. 15 tests were run for both the Oral B and Sonicare tooth brushes, as the AcceleDent unit does not touch the brackets while being used intra-orally. Like the other testing scenarios, the tooth brush was turned on just before the test began.

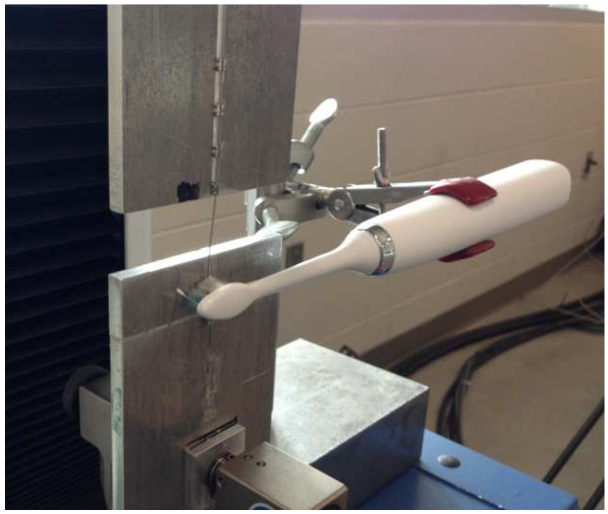


Figure 11. Sonicare tooth brush directly placed against test bracket/wire interface.

Frictional values were analyzed with statistical software using one-way analysis of variance (ANOVA) testing with independent variables being vibration source. Tukey *Post Hoc* comparison was used to find differences between the groups.

CHAPTER 4
RESULTS

The static and kinetic frictional values were recorded for each test over a 7 mm sliding distance (Blue hill).

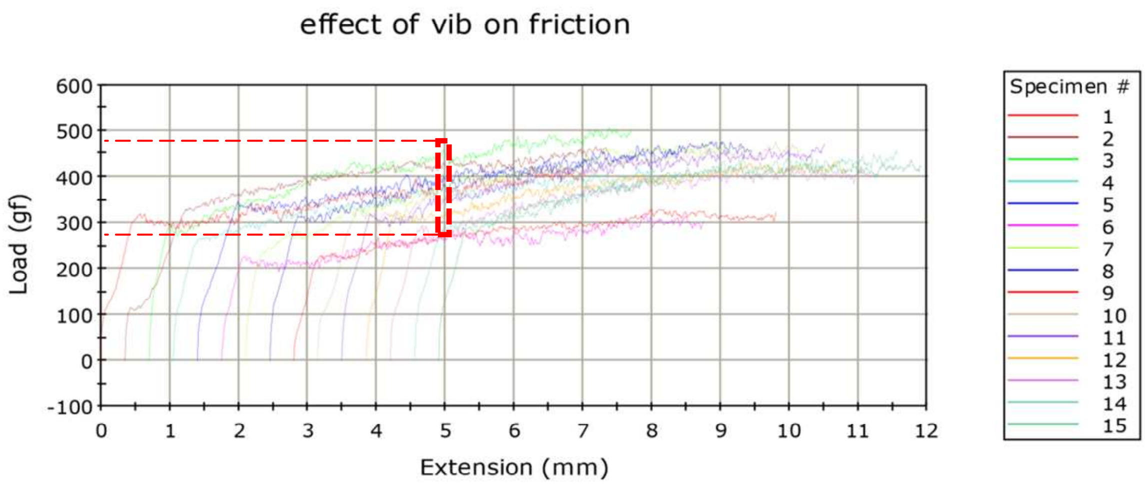


Figure 12. Static and dynamic frictions in the control group. Range of dynamic friction (by 5 mm): 267g (min) - 478g (max)

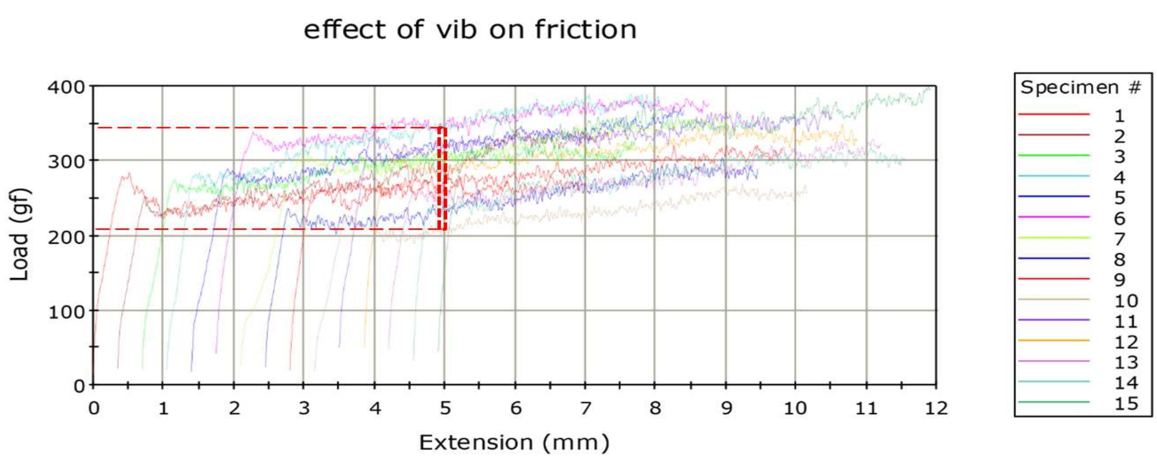


Figure 13. Effect of Vibration from AcceleDent on static and dynamic frictions in the experimental group. Range of dynamic friction (by 5 mm): 210g (min) - 345g (max).

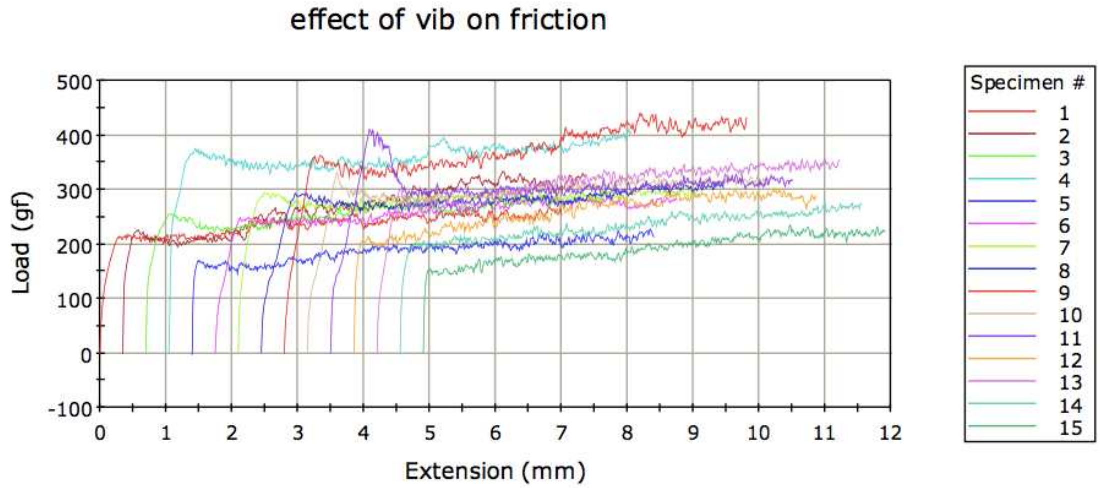


Figure 14. Effect of Vibration from Sonicare tooth brush (side of testing plate) on static and dynamic frictions in the experimental group. Range of dynamic friction (by 5 mm): 190g (min) - 379g (max).

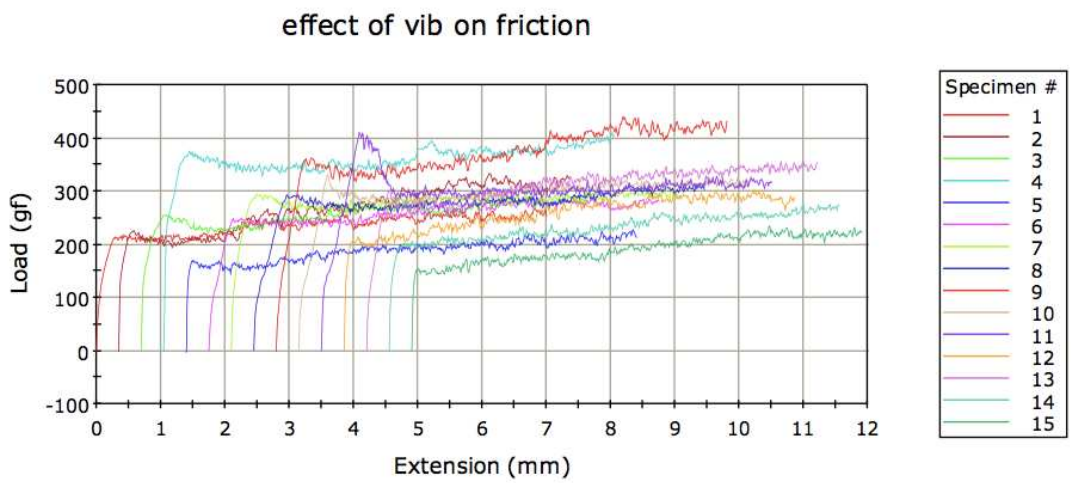


Figure 15. Effect of Vibration from Oral B tooth brush (side of testing plate) on static and dynamic frictions in the experimental group. Range of dynamic friction (by 5 mm): 267g (min) - 413g (max).

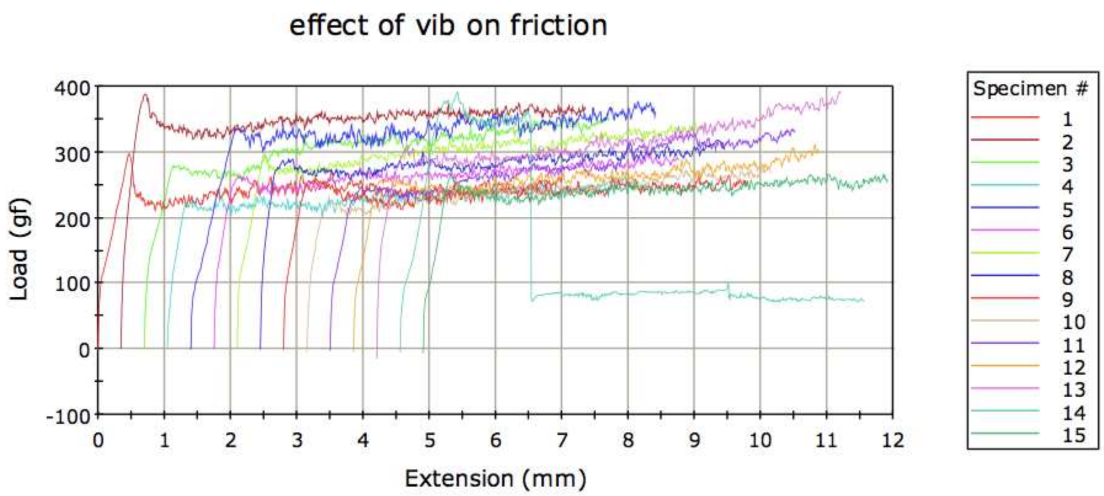


Figure 16. Effect of Vibration from Sonicare tooth brush (front of testing plate) on static and dynamic frictions in the experimental group. Range of dynamic friction (by 5 mm): 232g (min) - 362g (max). Trial 14 was discarded because of bracket bond failure during testing.

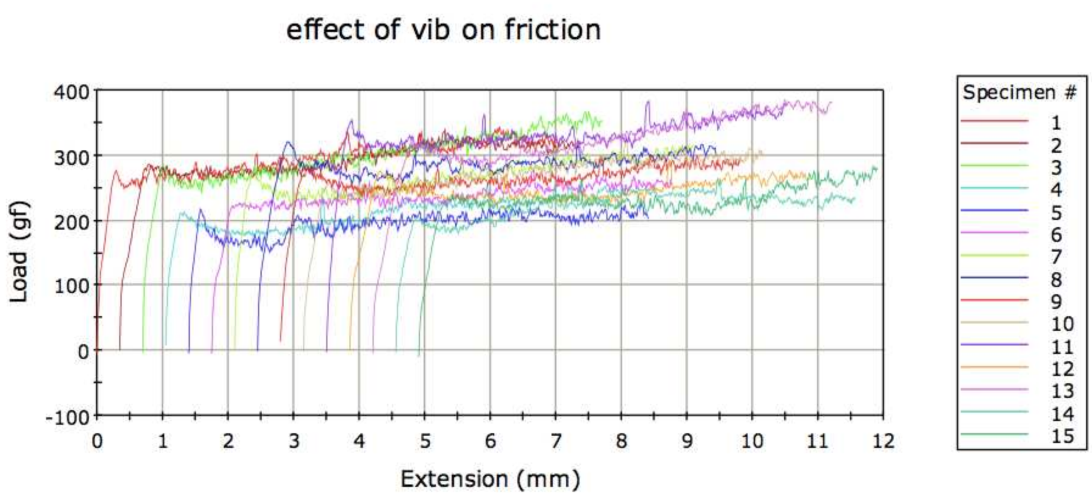


Figure 17. Effect of Vibration from Oral B tooth brush (front of testing plate) on static and dynamic frictions in the experimental group. Range of dynamic friction (by 5 mm): 211g (min) - 348g (max).

The above graphs are examples that show the force versus distance plots that were recorded for each set of experimental conditions. The static frictional coefficient was recorded for each specimen. This represented the force that it took to begin movement of the wire, while the kinetic frictional value was recorded at an arbitrary point 5 mm into the test (21).

The values for each of the tests are displayed in Tables 1-3, along with the mean and standard deviation of each vibrational testing source.

Table 1. Raw data for control values and AcceleDent values. Means and standard deviations are shown for each column**.**

Sample #	Control (Static)	AcceleDent (Static)	Control (Dynamic)	AcceleDent (Dynamic)
1	0.30725	0.2792	0.3777	0.25905
2	0.29662	0.25292	0.43076	0.30349
3	0.29662	0.27492	0.46495	0.31058
4	0.26528	0.28045	0.38387	0.36497
5	0.34522	0.28946	0.41873	0.33302
6	0.22758	0.31224	0.27271	0.36341
7	0.23447	0.14151	0.43622	0.33849
8	0.3144	0.23676	0.43529	0.26679
9	0.22889	0.2442	0.31089	0.29929
10	0.3277	0.22036	0.44825	0.24122
11	0.31897	0.33162	0.4303	0.3395
12	0.32349	0.30418	0.4072	0.33687
13	0.28335	0.25701	0.41407	0.2883
14	0.28695	0.23844	0.41619	0.30195
15	0.29052	0.31446	0.40433	0.3576
Mean	**0.28982**	**0.265182**	**0.403430**	**0.313635**
SD	**0.036635**	**0.047189**	**0.051111**	**0.038510**
%	100	91.50	100	77.74
% Change		-8.50		-22.26

Table 2. Raw data of control and tooth brush vibration from the side of the testing plates (KgF)

Sample #	Control (Static)	Oral B (Static)	Sonicare (Static)	Control (Dynamic)	Oral B (Dynamic)	Sonicare (Dynamic)
1	0.30725	0.25429	0.21672	0.3777	0.29396	0.24714
2	0.29662	0.21002	0.22417	0.43076	0.27281	0.30321
3	0.29662	0.33786	0.24901	0.46495	0.41362	0.25962
4	0.26528	0.32306	0.36053	0.38387	0.3536	0.37991
5	0.34522	0.27519	0.16393	0.41873	0.33153	0.19096
6	0.22758	0.31682	0.24833	0.27271	0.38896	0.27444
7	0.23447	0.22564	0.27488	0.43622	0.26785	0.28624
8	0.3144	0.25159	0.28769	0.43529	0.30902	0.29226
9	0.22889	0.21542	0.3612	0.31089	0.28806	0.40824
10	0.3277	0.25184	0.29408	0.44825	0.31849	0.31288
11	0.31897	0.15185	0.3106	0.4303	0.22277	0.3064
12	0.32349	0.23138	0.20746	0.4072	0.30989	0.28528
13	0.28335	0.22317	0.29773	0.41407	0.29944	0.32786
14	0.28695	0.25345	0.19776	0.41619	0.33219	0.24321
15	0.29052	0.19073	0.15456	0.40433	0.28997	0.20896
Mean	**0.28982**	**0.247487**	**0.256576**	**0.403430**	**0.312810**	**0.288440**
SD	**0.03663**	**0.050496**	**0.063639**	**0.051111**	**0.047662**	**0.057344**
%	100	85.40	88.54	100	77.54	71.49
% Change		-14.60	-11.46		-22.46	-28.51

Table 3. Raw data of control and tooth brush vibration from the front of the testing plates (KgF)

Sample #	Control (Static)	Oral B (Static)	Sonicare (Static)	Control (Dynamic)	Oral B (Dynamic)	Sonicare (Dynamic)
1	0.30725	0.26355	0.22109	0.3777	0.32144	0.2328
2	0.29662	0.26901	0.32907	0.43076	0.31935	0.36239
3	0.29662	0.2658	0.26595	0.46495	0.30875	0.31687
4	0.26528	0.19184	0.2158	0.38387	0.2291	0.23892
5	0.34522	0.21746	0.32749	0.41873	0.21142	0.33761
6	0.22758	0.22115	0.23983	0.27271	0.25361	0.27802
7	0.23447	0.2617	0.27498	0.43622	0.29665	0.31796
8	0.3144	0.28999	0.27233	0.43529	0.29303	0.28751
9	0.22889	0.25562	0.22963	0.31089	0.27426	0.24815
10	0.3277	0.24567	0.22587	0.44825	0.29237	0.24928
11	0.31897	0.31918	0.24034	0.4303	0.34893	0.30817
12	0.32349	0.25711	0.24598	0.4072	0.25069	0.2838
13	0.28335	0.3163	0.28074	0.41407	0.34876	0.33182
14	0.28695	0.18789	Debond	0.41619	0.2359	Debond
15	0.29052	0.2313	0.23658	0.40433	0.23368	0.24643
Mean	**0.289820**	**0.252904**	**0.25736**	**0.40343**	**0.28119**	**0.28845**
SD	**0.036635**	**0.03888417**	**0.03730**	**0.051111**	**0.04401**	**0.041358**
%	100	87.27	88.82	100	69.71	71.52
% Change		-12.73	-11.18		-30.29	-28.84

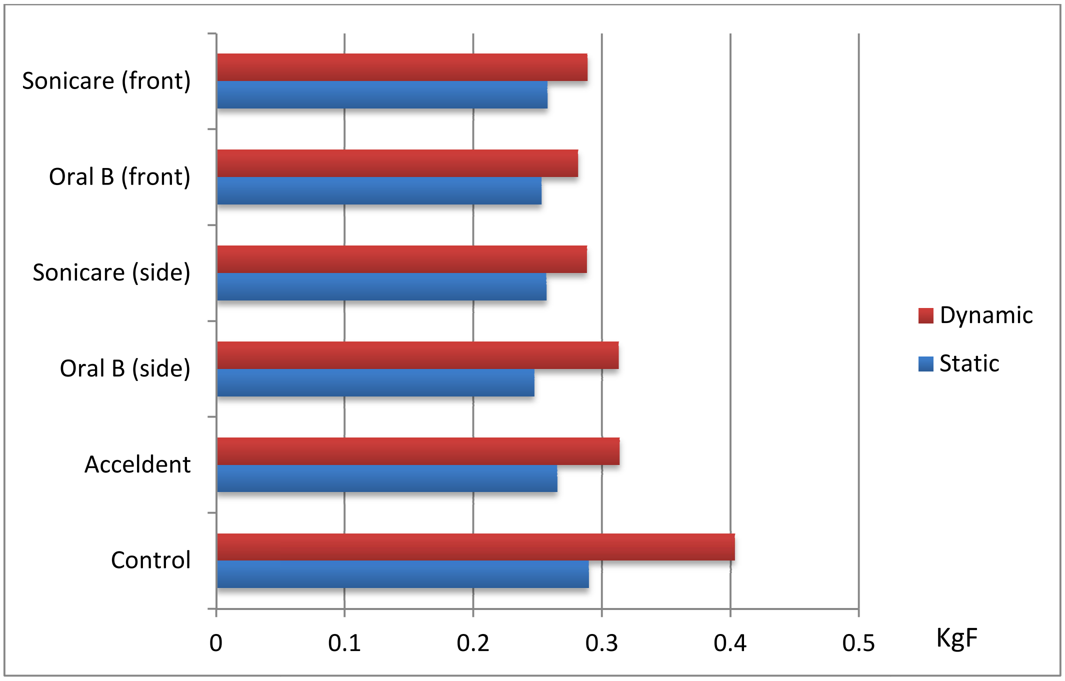


Figure 18. Static and dynamic friction values for all test conditions measured in kilograms force (KgF). Front depicts positioning the mechanical vibration device directly against the test bracket, while side was applying vibration to the plate.

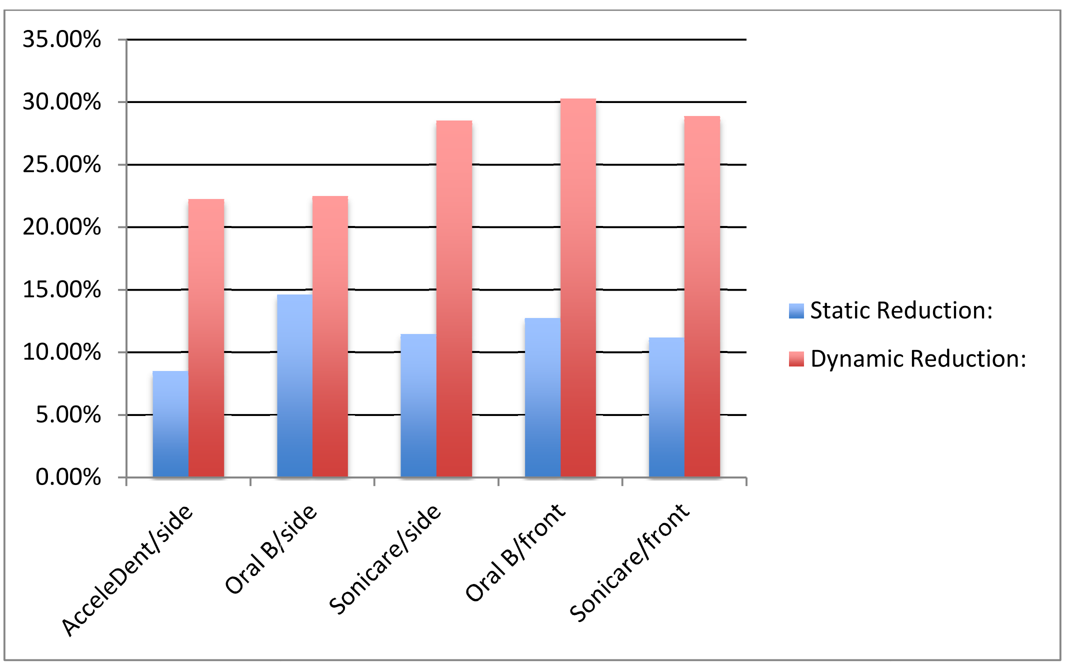


Figure 19. Percentage reduction of static and dynamic values for all test conditions.

CHAPTER 5
DISCUSSION

One of the criticisms of friction testing is that the studies are completed in a laboratory setting and not in vivo (3, 8). Testing vibration intra-orally exposes the study to many independent variables such as saliva, temperature, and various intra-oral movements that can affect the results. Many laboratory studies have already been completed comparing friction and these other independent variables; as a result of this, most of their effects on friction and sliding are already known. Testing mechanical vibration ex vivo allows the independent variables to be minimized. Clinical studies including vibration are also difficult to implement while also keeping an accurate study design. Testing mechanical vibration intra-orally would be difficult because a single source of vibration translates across the arch (22). So using a split mouth design would not be appropriate, as the vibration from the testing side would also be felt on the control side. For this study, an *ex-vivo* testing set up allows the concept of mechanical vibration (and not perturbations) to be tested and specific independent variables to be isolated. The materials selected for this study were chosen in order to best represent the clinical scenario of leveling and aligning; and the phenomenon of binding which accounts for most of the resistance to sliding in the fixed appliance system (6). In accordance with previous friction testing studies (21), the brackets used in this study were conventional stainless steel twin brackets with 0° tip and 0° torque. This eliminated the effect of 3rd order binding, which can be different depending on bracket prescription and wire dimensions (9). Conventional brackets were chosen over self-ligating because the ligation method does not affect the amount of binding that takes place at the bracket-wire interface (6, 17). Conventional brackets are also one of the more common fixed appliances being used in clinical orthodontics, giving this study broad applicability to the majority of clinicians. The wires used for testing were chosen in part due to the study design; since bracket offsets were used in the study, the wire chosen for testing needed flexibility and minimal rigidity in order to emulate a true clinical situation of leveling and aligning. Due to limited manufacturing of straight NiTi wire segments, .016” X .022” rectangular wire was used for testing. Choosing the crosshead speed of 5 mm/min was based on previous studies (Table 4) and the work of Kusy *et al.* who found that the frictional coefficients were not affected by a change in sliding resistance when using stainless steel brackets (23).

Table 4. Previous friction studies showing crosshead speed used

Study	**Sample Size**	**Crosshead speed:**
Braun (1999)	8 tests/condition	.1mm/min
O'Reilly: (1999)	20 tests/condition	1mm/min
Thorstenson (2002)	5 tests/condition:	10mm/min
Krishnan(2009)	10 tests/condition	5mm/min
Olson (2012)	5 tests/condition	N/A

The number of tests chosen for each condition was also chosen based on previous landmark friction/vibration studies (Table 4). Fifteen new tests were run for each new set of conditions.

The three clinical devices had various outputs for amplitudes and frequencies (Table 5).These were applied to the test plates just as they would be intra-orally. Previous studies have a range of vibrational frequencies shown in Table 6.

Table 5. Frequency measurements of the clinical devices tested

Oral B	250hz
Phillips Sonicare	255hz
AcceleDent	30hz

Table 6. Previous vibration studies and frequencies used for testing

Nishimura	60hz
Iwasaki	60hz
Liew	90hz
Olson	60-140hz

The results show that all of the mechanical vibration devices tested significantly reduce the sliding resistance when compare to the control group. These findings are consistent with most of the previous studies in this area when related to non-mechanical vibration (3, 9, 17). However, there are slight differences in study designs and testing parameters in those studies. Several studies found a reduction in the frictional resistance with the application of perturbations, either in the form of finger pressure (17) or mastication movements (3) that were tested intra-orally. Iwasaki *et al*. did not find a reduction in frictional resistance with their intra-oral experiment involving perturbations. These conflicting results mean that orthodontic patients may or may not be reducing the sliding resistance in their fixed appliances by masticational forces and intra-oral movements. *Iwasaki et al*. proposed that a reduction of frictional forces intra orally might depend on the length of chewing or the amount of mechanical energy put into the system (force of chewing) (10). Chewing more frequently or with more force could cause a reduction in the resistance to sliding, but it could also be associated with negative consequences such as loose brackets and broken appliances. With the addition of mechanical vibration to the fixed appliance system, there could be an additional benefit of reduced sliding resistance without the negative consequences of increased risk of de-bonded brackets.

The results of this study were also unique because resistance to sliding was tested under a simulated clinical binding scenario, which has been shown to be the most important contributor to the overall resistance to sliding (24). Previous studies used mainly stainless steel wires for their testing, which tested a purely frictional component that is seen more during space closure. Using straight pieces of NiTi wire allowed for the flexibility needed to fully engage the offset test bracket and obtain true binding. Although Braun *et al*. varied the angulation of the test bracket, which introduced some binding to the system; the study did not have a terminal bracket beyond that of the test bracket. This does not emulate a true clinical situation where there is a bracket on either side of the tooth being tested. Our study had a terminal bracket which eliminated the cantilever design produced in previous studies.

Not only did this testing set up mimic a clinical binding scenario, it was also able to incorporate a PDL replica, which allowed for mimicking physiologic movement of the test bracket. This addition to the standard testing set up was advantageous over previous studies. O’Reilly *et al.* incorporated a two-piece system with the test bracket on a swivel-mounted fixture. The vibration source was then applied to the metal fixture that held each test bracket; this method used by O’Reilly *et al*. worked to produce vertical displacement of the test bracket. It was decided that in order to more closely resemble a true bracket/tooth system, the natural frequency of the PDL would be used to select a suitable material incorporate between the testing plates.

Despite the variation of frequency output from the three testing devices, each of them was able to significantly reduce the sliding resistance. The minor differences between the three forms of vibration were not significant (Tukey *Post Hoc* analysis). This means that all three of the mechanical vibration devices produce the same reduction in sliding resistance and it cannot be said that one of the devices is superior. Frequencies of 30 Hz from the AcceleDent unit produced the same reduction in the sliding resistance as the higher frequency devices from the tooth brushes (250 Hz). These findings conflict with earlier results by Olson *et al.* who found that frictional resistance was not significantly affected by the frequency of arch-wire vibrations. They instead found that medium and high-level amplitudes were responsible for significant changes in frictional resistance (3). Our study shows that there is a range of frequencies that all reduce the sliding resistance when compared to control values. Due to the fact that all mechanical vibrations devices being tested were from specific manufacturers, the amplitude was unable to be changed or measured, as this is not normally a metric that commercial companies use to quantify their vibration. Future studies could incorporate similar products that have varied their amplitude output, as this could also affect the reduction in sliding resistance when applied fixed appliance system.

There was no statistically significant difference between the locations of vibration on the testing plates. Positioning the tooth brushes on the side of the plate (mimicking the side or occlusion surface of a tooth) seemed to have the same effect as positioning them against the bracket (mimicking the direct contact that the bristles have against the bracket/arch wire interface). This means that the mechanical vibration applied to the plates was able to translate across the entire testing surface, so the point of application did not affect the results. This finding is supported by the work of Liu *et al*., who found mechanical vibration could translate across the arches and was independent of application point (22). Although the application point of the tooth brush head was designed to mimic a clinical situation in which the tooth brush contacts the bracket and arch-wire in addition to the teeth, this study did not account for the movement of the tooth brush in relation to the patient's hand. In order to have consistent measurements, the tooth brush was mounted and kept at this position for all the testing. The tooth brush was unable to move during the testing; if movement of the tooth brush was allowed when testing, perturbations would then also be introduced to the system. This idea could be incorporated into future studies to see if mechanical vibration and perturbations from the tooth brush against the brackets would have any additional effect.

While the results of this study show that mechanical vibration does reduce the resistance to sliding in the fixed appliance, it cannot be directly inferred that this will reduce treatment time when applying the concepts to clinical cases. Similar to perturbations from mastication and other movements, mechanical vibration will only enhance the mechanics that are being used, whether those are desired or undesirable forces (1). One of the potential benefits of using mechanical vibration as an adjunct to treatment is the additive effect it will have on reducing sliding resistance and releasing the binding that occurs clinically during leveling and space closure scenarios. Clinicians would also not have to rely on patients chewing carrots or something hard enough to produce the mechanical energy needed to cause reductions in sliding; as these could have an increased chance of de-bonding brackets.

This study was one of the first to test mechanical vibrations from commercially available products and test their effect of the sliding resistance in the orthodontic fixed appliance. Future studies in this field should be focused on both *in-vivo* and *ex-vivo* experiments. Variation of the amplitude and frequency of the commercial devices could be tested *ex-vivo* to determine if any further reduction in sliding can be obtained. When increasing these values, their effects on the biological system should also be taken into account; increasing the amplitude and frequency to completely reduce sliding resistance could be possible, but it might not be tolerable or healthy for the patient. If optimal values for amplitude and frequency are found in bench-top testing, these values could then be tested in a biological way to verify their affects.

In addition to testing new combinations of output frequency and amplitude from the commercial devices, improvements to the testing set up can also be made for future studies. Modifications were made to the "standard" friction testing set up, including the addition of a binding component and PDL replica. Future studies should incorporate binding in the testing set up by either bracket offsets or change in bracket angulation. Incorporating a rotational component to the test bracket as shown in O'Reilly *et al*. would allow testing of bracket angulations at consistent angles. The reliability of the testing set up could also be improved by fabrication of a mounting jig, which would decrease the amount of operator error found in mounting the test brackets. Bonding the brackets with a stiff piece of SS wire is an acceptable method for testing, but there could be some component of angulation introduced with this method.

Future studies should also include a PDL replica material that enables all test brackets to have physiologic mobility. This study can serve as a starting point for exploring additional designs and materials used for testing.

CHAPTER 6
CONCLUSION

1. All mechanical vibration devices tested show statistically significant reductions in the resistance to sliding in the orthodontic bracket-wire interface when compared to the control group.

2. There are no statistically significant differences among the three devices in reducing the sliding resistance.

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