Friction Testing of a New Ligature

Alison Mantel
Marquette University

FRICTION TESTING OF A NEW LIGATURE

by

Alison R. Mantel, DDS

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ABSTRACT
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Objective: To determine if American Orthodontics' (AO) new, experimental ligature demonstrates less friction in vitro when compared to four other ligatures on the market.

Methods: Four brackets were mounted on a custom metal fixture allowing an 0.018-in stainless steel wire attached to an opposite fixture with one bracket to be passively centered in the bracket slot. The wire was ligated to the bracket using one of five types of ligatures including the low friction test ligatures (AO), conventional ligatures (AO), Sili-Ties™ Silicone Infused Ties (GAC), Synergy® Low-Friction Ligatures (RMO), and SuperSlick ligatures (TP Orthodontics). Resistance to sliding was measured over a 7 mm sliding distance using a universal testing machine (Instron) with a 50 Newton load cell and a crosshead speed of 5 mm/min. The initial resistance to sliding (static) was determined by the peak force needed to initiate movement and the kinetic resistance to sliding was taken as the force at 5 mm of wire/bracket sliding. Fifteen unique tests were run for each ligature group in both dry and wet (saliva soaked for 24 hours with one drop prior to testing) conditions.

Results: In the dry state, the SuperSlick ligature demonstrated more static friction than all of the other ligatures, while SuperSlick and Sili-Ties demonstrated more kinetic friction than the AO conventional, AO experimental and Synergy ligatures. In the wet condition, SuperSlick and the AO experimental ligature demonstrated the least static friction, followed by the AO conventional and Sili-Ties. The most static friction was observed with the Synergy ligatures. In the wet condition, the SuperSlick, AO experimental and AO conventional exhibited less kinetic friction than the Sili-Ties and Synergy ligatures.

Conclusions: AO's experimental ligature exhibits less friction in the wet state than conventional ligatures, Sili-Ties and Synergy and is comparable to the SuperSlick ligature. These preliminary results suggest that the AO experimental ligature and the SuperSlick ligature create less friction, but direct conclusions regarding in vivo performance cannot be made and randomized controlled clinical trials are needed to determine if these ligatures have clinical significance in treatment efficiency.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION & LITERATURE REVIEW

One of the primary goals in orthodontics is to provide the most efficient tooth movement possible. This quest for efficiency has inspired the development of countless materials in orthodontics aimed at reducing treatment time. Although self-ligating brackets have been available since the 1930's, there has been a recent resurgence in their popularity in the past decade. Due to this attention, the topic of friction and treatment efficiency has once again surfaced to the forefront of many literary publications and discussions.

Orthodontic treatment with fixed appliances involves the use of metal, ceramic or plastic brackets in combination with metal archwires. The brackets have slots for the archwires and tie wings to allow ligatures to affix the archwire to the bracket. Traditionally ligatures were made of stainless steel (SS), however due to the length of time these ligatures take to place; an improved material was sought out. In the 1960's, Drs. Anderson and Klein, patented a doughnut-shaped flat ring of circular cross section, made of an elastomeric polymer such as polyurethane which is compatible with the environment of the mouth.[1] The manufacturing process involved injection molding elastomeric, polyester based, isocyanate terminated, urethane resin.[1] Elastomeric ligatures gained general acceptance in orthodontics due to their ability to quickly stretch over the bracket, thereby decreasing chair time and increasing patient comfort. In an attempt to decrease areas of decalcification around brackets, flouride-releasing ligatures were developed in the 1990's. Flour-I-Ties (Ortho-Arch Company Inc) are manufactured with stannous fluoride (SnF_2), however studies indicated the fluoride release consisted of a burst within the first couple of days and resulted in 88% fluoride loss after just two weeks[2] and an in vivo study indicates that they do not significantly lower Streptococcus mutans levels 7, 14 and 28 days after placement.[3] In 2001, Logan patented a ligature with an arch or curve on one side to simplify and speed tying in the archwire.[4] Due to the high contact adhesiveness of polyurethane ligatures to metal archwires, some ligatures have been manufactured with the aim of decreasing the coefficient of friction to facilitate easier movement of the archwire along the brackets. Specific manufacturing techniques for these ligatures include injection molding of silicone based materials or adding specialized hydrophilic coatings.

Friction is the force resisting the relative lateral motion of solid surfaces, fluid layers, or material elements in contact. Friction is not a fundamental force. It is derived from the electromagnetic force between charged particles such as electrons, protons, atoms and molecules.[5] Friction is usually subdivided into several varieties including dry, fluid, skin, and internal friction. Orthodontic friction involves the interaction between the bracket slot, the wire and the ligator and is considered to be in the category of dry friction among the varieties mentioned above. Dry friction resists the relative lateral motion of two solid surfaces in contact. When two materials slide across one another, contact occurs only at the microscopic peaks on the surfaces. These peaks are called asperities.[5] Dry friction can be classified as either static or kinetic friction. Static friction is friction between two solid objects that are not moving relative to each other. Its magnitude is what is required to oppose motion up until movement starts. Kinetic friction occurs when two objects are moving relative to one another. It is usually less than static friction.[5] Kinetic friction is less relevant to orthodontics because continuous motion along an archwire never occurs.[5] Tooth movement occurs at approximately 1 mm per month, or 0.23×10^{-4} mm per minute,[6] making the process closer to a scenario in which static friction is more relevant. The resistance to tooth movement involves more than friction alone, however.

Kusy and Whitley partitioned the resistance to tooth movement into three separate components.[7] The first component is classical friction that occurs between the wire and bracket surfaces and is further divided into static and kinetic friction. The second component is binding that occurs when a tooth is tipped or a wire is flexed so that the wire contacts the corner of the bracket. The third component is notching. This is permanent deformation of the wire at the wire-bracket interface that stops tooth movement until the notch is released. Thus, resistance to tooth movement is equal to the sum of friction, binding and notching and this is applicable in both passive and active configurations. Passive configurations are those in which the contact angle (θ) between the archwire and bracket slot is less than the critical contact angle (θ_c). When passive, only classical friction controls sliding mechanics because binding and notching are not occurring. As the contact angle between the wire and bracket increases, friction becomes less relevant and binding and notching become greater forces resisting movement.[7] Classical friction controls sliding mechanics only when the contact angle between the bracket and wire is less than 3.7 degrees.[7]

Friction can be a simple component of orthodontics to study, but it is difficult to do so in a way that emulates the true intraoral experience. Methods to study friction in vivo have been developed, but the preponderance of the evidence consists of in vitro studies due to their simpler design.[5] There are numerous limitations to in vitro studies.

First, the majority of investigations are passive systems in which the binding and notching components have been removed, leaving only a study of pure friction. These studies mount a bracket so that the wire is pulled through it completely parallel to the slot without introducing any angulation between the wire and the bracket (Figure 1).

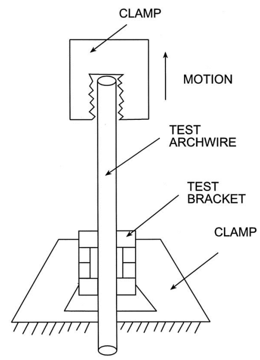

Figure 1. Example of a passive, in vitro friction study set up.[6] Reprinted with permission

They measure only the amount of friction that is between the wire, bracket and the ligature or self-ligating apparatus. The advantage to these studies is they determine the amount of friction contributed by the type of ligator, bracket and wire without other variables involved. The disadvantage is that in many clinical situations, the brackets are placed in positions that are far from passive to one another.

Nicolls[8] first reported in 1968 that resistance to sliding increases as the contact angle between the bracket and the archwire increases. Other studies have since confirmed this finding[9-13] and in 1999, Articolo and Kusy[14] compared resistance to sliding in passive ($\theta = 0$) versus active ($\theta > 0$) configurations with varying bracket and archwire materials. When the angulation between the bracket and the archwire exceeded just 3°, binding equaled or exceeded friction. Binding made up at least 80% of the resistance to sliding at $\theta = 7°$ and as much as 99% at $\theta = 13°$ for a stainless steel wire in a ceramic bracket. Due to the importance of binding in the study of resistance to sliding, many friction studies have attempted to add the component of varying angulations between the wire and bracket slot.

For example, Franchi et al.[15] conducted an in vitro study attempting to reproduce the right buccal segment of the maxillary arch to compare a nonconventional elastomeric ligature (Slide, Leone Orthodontic Products) with a conventional elastomeric ligature. Five stainless steel 0.022 x 0.028-in preadjusted brackets were mounted 8.5 mm apart, with the canine bracket welded to a sliding bar (Figure 2). The study then tested the forces released by the system after 1.5, 3, 4.5 and 6 mm of vertical canine displacement. The authors noted that the major limitation to this study was the inability of the other brackets contiguous to the misaligned bracket to move, mimicking an absolute anchorage scenario.

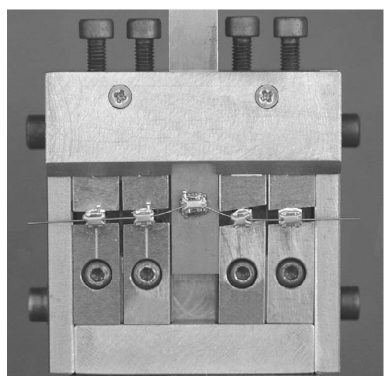

Figure 2. In vitro test of misaligned canine bracket.[15] Reprinted with permission.

A second limitation to the passive in vitro friction studies is the absence of minor perturbations or disturbances that are normally produced by various oral functions. When a person speaks, chews and swallows or when tissues or food contact the dentition or orthodontic appliance, random minute movements occur within the appliance and shift the archwire in the bracket slot. This shifting has been shown to alter the friction in the appliance. Braun et al.[6] were the first to complete a pilot study attempting to measure this aspect. They mounted six brackets at angulations from 0° to 25.5° (Figure 3) and pulled three different size stainless steel wires through them with an Instron while applying simulated oral perturbations. The perturbations were finger pressures of 87.2 grams applied to the bracket or arch wire in random frequencies and directions in three planes of space. They found that perturbations caused the frictional resistance to momentarily become zero in 95.8% of their 48 experiments. Factors such as the ligator, archwire/slot clearances and bracket angulation did not have a measureable effect on friction when stimulated with these perturbations. If the average frequency of masticatory contacts is 32 to 80 cycles per minute,[16] these reductions in friction may be a significant part of the equation. It was noted that the resistance was reduced to zero because the binding and notching occurring at the bracket/archwire interface was released temporarily. They summarized their findings with the statement, "This pilot study demonstrates that a preponderance of in vitro frictional resistance experiments conducted in the past do not reflect the mode of frictional resistance that may actually occur in the oral cavity, and that random, intermittent, repeated, minute relative motions at the bracket/arch wire interface significantly decreased, if not completely eliminated frictional resistance. This occurs on a cyclical basis as one chews, speaks, swallows, etc, and as the tissues, food, etc contact the orthodontic appliance."[6]

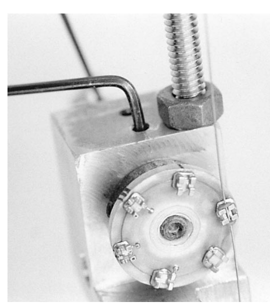

Figure 3. Test brackets in a jig that permits angular changes with a center of rotation of 10 mm.[6] Reprinted with permission.

Until recently orthodontic force systems were limited to 2-dimensional experimental studies. However, in 2009 Badawi et al.[17] designed a 3-dimensional computer model capable of accurately measuring forces and moments applied by orthodontic appliances on all of the teeth in a single arch. Already available 3D sensors, called multi-axis force transducers, were reproduced at a much smaller scale so that they could be fixed to individual teeth.

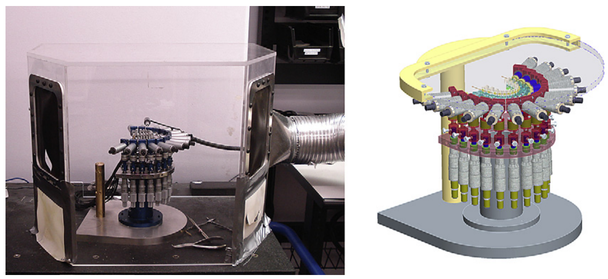

Figure 4. Orthodontic Simulator.[17] Reprinted with permission.

The objective of the study was to understand the force system at the bracket-wire interface, not to accurately simulate the oral environment. The authors noted that this device does not control all of the possible intraoral variables such as moisture, lip pressure, tongue pressure, PDL compliance, and alveolar bone level and geometry. In spite of these limitations, this machine may improve the quality of future in-vitro experiments.

Many studies have been conducted that evaluate the various factors influencing frictional resistance in orthodontics including relative bracket/arch wire clearances, arch wire size related to its stiffness, round versus rectangular wire, torque at the wire bracket interface, surface conditions of the arch wires and bracket slots as related to the material they are composed of, relative motion at the bracket/wire interface, and type and force of ligation.[6] Some of these variables have been measured in numerous studies and often a clear consensus has been reached. Stainless steel wires provide the least amount of friction, β-Titanium the greatest and nickel-titanium in between.[10,18,19-25] Stainless steel brackets produce less friction than ceramic brackets.[20,21,23,25-27] However, ceramic brackets with a metal slot may exhibit similar amounts of friction when compared to stainless steel brackets.[28] The greater the angulation of the archwire in the bracket slot, the higher the friction.[9,10,20,27] Some factors relating to friction show conflicting evidence including the effects of lubrication,[7,8,20,23,25,27,29,30] bracket size,[8-10,18,19,22] and size of the archwire.[10,11,18,20,21,24,31-33] There are many different types of ligators in orthodontics including conventional elastomeric ligatures (CEL), nonconventional elastomeric ligatures (NCEL) that are lubricated elastomeric modules, loosely tied stainless steel ligatures, active self-ligating brackets and passive self-ligating brackets. All of these materials exhibit differing amounts of friction. Possible benefits of a nonconventional elastomerics include decreased cost in comparison to self-ligating brackets and the ability to apply friction and low-friction mechanics simultaneously and selectively on each patient.

Hain et al.[34] demonstrated that when the bracket and archwire angulation is carefully controlled, friction is significantly affected by the ligation method. They compared two self-ligating brackets (Damon 2 and Speed) with four conventional ligatures (TP Orthodontics (TP) regular, conventional and Easy-To-Tie by 3M Unitek, and American Orthodontics (AO) standard and two nonconventional ligatures (SuperSlick (TP) and Sili-Ties (GAC)). The study found that the SuperSlick ligatures produced 50% less friction than all of the other ligation methods except Damon 2. Damon 2 had no recordable friction of ligation. There was no statistical difference between the Sili-Ties, Easy-To-Tie and TP regular. The AO standard and 3M Unitek conventional produced statistically more friction than all of the others. Sixty minutes of exposure to saliva significantly reduced friction in coated modules. Prolonged exposure to saliva (one week) reduced friction in regular uncoated modules, but they still had 50% more friction than coated modules. There was no statistical difference between sixty minutes and one week of saliva exposure for coated modules.

In a prior study, Hain et al.[29] compared conventional ligatures, stainless steel ligatures, and SuperSlick (TP) on twin, miniature twin, and metal-reinforced brackets. Also included was the friction produced by the Speed self-ligating bracket. They found that the loosely tied (tied tightly and unwound three times) stainless steel ligatures produced almost no friction, followed by the Speed brackets. The SuperSlick modules reduced static friction by up to 60% compared with the conventional ligatures regardless of the bracket system used. The reduction of friction when lubricated was greater for the SuperSlick ligatures (50-60%) than for the conventional modules (10%-30%). While the results looked promising for the stainless steel ligatures, the authors note that this may be negated by the amount of time needed to tie all of the brackets in with this method and problems associated with an archwire that is not completely engaged in the slot.

Griffiths et al.[26] did not find that frictional resistance to sliding was less with TP's SuperSlick ligatures. In their study they found that self-ligating brackets produced almost no friction, and in all but 2 combinations, round conventional modules provided the least amount of friction, followed by SuperSlick, with rectangular shaped elastomeric modules showing the most friction. However, their wet state conditions consisted of soaking the ligatures for one hour in a 37°C hot water bath instead of the use of real or artificial saliva, thus it cannot be directly compared to other studies.

Khambay et al.[35] investigated the effect of various forms of ligation on friction as well. They included four types of elastomeric modules: purple, grey, Alastic (Unitek ligatures with a 45 degree bend), SuperSlick, as well as stainless steel ligatures and Damon 2 brackets. They studied this on TMA and stainless steel wires of 017 x 0.025-in and 0.019 x 0.022-in sizes. They concluded that the Damon 2 bracket produced negligible levels of friction and that it is the only way to truly eliminate friction contributable to the ligator in the system. The SuperSlick modules did not produce the lowest levels of friction. The metal ligatures with seven turns produced the lowest friction in all wires but the 0.017 x 0.025-in TMA. The purple modules produced the lowest friction only on the 0.017 x 0.025-in TMA wire. The 45 degree bend in the Alastic module did decrease friction on the 0.019 x 0.025-in SS wire to that of the steel ligatures, but did not decrease friction with the other types of wire. In this study, the ligatures were not soaked in saliva for any length of time, but were given 1 ml/minute of human saliva from a syringe during testing.

The Slide ligature (Leone Orthodontic Products, Sesto Fiorentino, Firenze, Italy) is manufactured with a special polyurethane mix by injection molding. When tied to the bracket and archwire, its shape allows the wire to slide through its tubelike slot with less resistance (Figure 5).

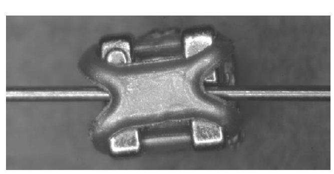

Figure 5. The Slide ligature by Leone Orthodontic Products. Reprinted with permission.[15]

Franchi and Baccetti have produced several studies aimed at determining the frictional forces produced by the Slide ligature.[15,37-39] As mentioned previously, in all three studies they used an experimental model reproducing the right buccal segment of the upper arch (from the maxillary right second premolar through the right central incisor) bonded with five stainless steel 0.022 x 0.028-in preadjusted brackets. In their initial study with this device, they compared a conventional ligature with the Slide ligature under dry conditions.[38] They measured the amount of static and kinetic friction with aligned brackets and a 0.0195 x 0.025-in stainless steel wire. They also measured the static and kinetic friction produced by a 0.014-inch superelastic nickel titanium wire in the presence of aligned brackets and of a canine bracket misaligned 3 mm. The results indicated that the Slide ligature produced significantly lower levels of friction with aligned and misaligned brackets. With the aligned brackets, the static and kinetic friction measured less than 10 g. with the Slide ligature and ranged from 95.6 g. for the 0.014-in nickel titanium wire to 590.7 g. for the 0.019 x 0.025-in stainless steel wire with the conventional ligature. The amount of both static and kinetic friction in the presence of the misaligned canine bracket was less than half in the Slide group than the conventional ligature group.

Following this study, Franchi and Baccetti redirected their focus from studying the friction produced by pulling the archwire through a series of brackets to examining the role of nonconventional ligatures in allowing the expression of orthodontic forces during alignment.[15] Thus the greater the force measured, the more the ligature allowed the expression of the archwire to align the brackets. Conventional ligatures and Slide ligatures were compared using 0.012-in, 0.014-in and 0.016-in nickel titanium wire with four different amounts of canine displacement: 1.5, 3, 4.5 and 6 mm. With a 1.5 mm misaligned canine bracket, the forces produced with the conventional and Slide ligatures were similar. However, for all other levels of displacement above this, the Slide ligatures allowed significantly greater levels of alignment forces. While this offers promising results, several limitations were noted. The testing machine did not allow the brackets contiguous to the misaligned bracket to move, mimicking an improbable absolute anchorage scenario. No attempt was made to mimic intra oral conditions with temperature, time or saliva. Lastly, at all four amounts of canine displacement, the contact angle (10°-35.2°) exceeded the critical contact angle (2.7°-4.5°) and the machine may have been testing binding conditions.

Most recently, Franchi et al. tested an even greater range of materials with this setup.[39] Seven bracket-ligature combinations were tested: 4 passive self-ligating brackets including Carriere (Ortho Organizers), Damon 3 MX (SDS Ormco), SmartClip (3M Unitek), and Opal-M (Ultradent Products), Synergy brackets with Synergy low-friction ligatures (Rocky Mountain Orthodontics), Logic Line conventional stainless steel brackets with Slide ligatures (Leone Orthodontic Products) and conventional stainless steel brackets with conventional elastomeric ligatures (Leone Orthodontic Products). 0.012-in and 0.014-in nickel-titanium wires were tested. The canine bracket was displaced by the Instron machine at four different levels of buccal misalignment: 1.5, 3.0, 4.5 and 6.0 mm. Each combination was tested 20 times. A similar result was found to the previous study demonstrating that with both types of wire all low friction systems (self-ligating brackets, Synergy and Slide ligatures) produced significantly greater forces for tooth alignment than the conventional systems at all amounts of canine displacement above 1.5 mm. When the displacement was greater (4.5 and 6.0 mm), the low friction systems produced a significant amount of force, but the conventional systems dropped to 0 g. They concluded that for buccal misalignments of 1.5 and 3.0 mm, both low friction and conventional systems are effective in releasing forces for tooth movement (30 to 60 g.), however when the displacement is larger than this, the forces for alignment are greater with low friction systems.

Gandini et al.[36] reported that self-ligating brackets (SmartClip, 3M Unitek) and the Slide ligature on conventional brackets with both 0.014-in NiTi and 0.019 x 0.025-in SS wire produced significantly lower levels of friction (0.1 g. to 1.2 g.) compared to conventional ligatures on conventional brackets (86.7 g. to 177.4 g.). Kahlon et al[40] tested five ligation methods (stainless steel, conventional ligatures and Slide ligatures on conventional brackets, Damon MX (Ormco) and In-Ovation R (GAC)) and 2 wire sizes (0.016 x 0.022-in and 0.018 x 0.022-in) with respect to their effects on frictional resistance. They concluded that the Slide ligature showed less friction at both wire sizes than conventional ligatures, however it showed significantly more friction than both Damon MX and stainless steel ligatures. Damon MX and stainless steel ligatures on conventional brackets produced no measurable friction with either 0.016 x 0.022-in or 0.018 x 0.022-in wires. For all ligatures, an increase in wire size demonstrated an increase in friction (with the exception of the Damon MX and the stainless steel ligatures which had no friction). Jones et al.[41] demonstrated that the Slide ligatures produced significantly lower static frictional resistance than conventional elastomeric modules in the dry condition and after 24 hours of storage in artificial saliva. Friction was measured along 0.018-in SS and 0.019 x 0.025-in SS wires in a passive system of stainless steel brackets with no torque or tip. They determined that the artificial saliva had no effect on the friction for either type of ligature.

As with most research, the wide variation in methodologies makes direct comparison amongst these studies difficult. There are many different types of brackets, numbers of brackets, wire sizes, types and timing of lubrication, and machine sizes and settings used throughout the literature. It also is extremely difficult, if not impossible, to test in vivo, so no direct comparisons can be made as to what happens in a patient's mouth for the approximate six weeks the ligature is working. There are no systematic reviews pertaining directly to the type of elastomeric ligature and its effect on friction at this time. Due to these discrepancies in methodology and the lack of high levels of evidence, no definite conclusions can be made on which ligature has the lowest level of friction and if it has clinical significance.

Recently, American Orthodontics has developed a new, experimental ligature. Although the composition of the ligature remains proprietary, it is believed to possess favorable friction properties compared to some of the ligatures mentioned above and advertised as low friction. The objective of this research was to compare the static and kinetic friction of this experimental ligature to that of a conventional ligature from American Orthodontics as well as three other low friction ligatures on the market.

MATERIALS AND METHODS

Auxillary materials used for testing friction in this study are displayed in Figure 6. Straight lengths of stainless steel wire (0.018-in round, item #856-618; American Orthodontics, Sheboygan, WI) were cut into 3.5 cm long pieces. All brackets used were 0.022 x 0.028-in slot stainless steel twin brackets with zero degrees of torque and tip (item #380-0021; American Orthodontics). Prior to testing, all as-received wires and brackets were cleaned with 95% ethanol.

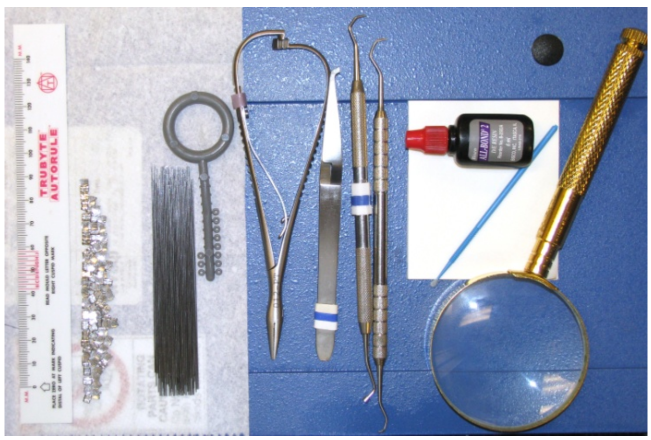

Figure 6. Materials used for the study. From left to right: Millimetric ruler, brackets, wires, ligatures, Matthau pliers, bracket holder, scaler, ligature director, bonding resin, magnifying glass.

Two custom metal fixtures were fabricated by cutting a groove the width of the bracket down the center of the plate. On one plate, an individual metal bracket was mounted in the groove using Clearfil Protect Bond dental bonding agent (Kuraray Medical Inc. Okayama, Japan) or All-Bond 2 D/E Resin (Bisco, Inc., Itasca, IL). For the testing described below, this bracket was tied with the ligature to be tested. After each test, the bracket was replaced, and the bonding agent was cleaned off the plate with a scaler. On the second plate, four brackets were equally spaced apart and adhered in the same fashion (Figure 7). All bonded brackets were light cured for 60 seconds (Optilux 501; Kerr, Danbury, CT).

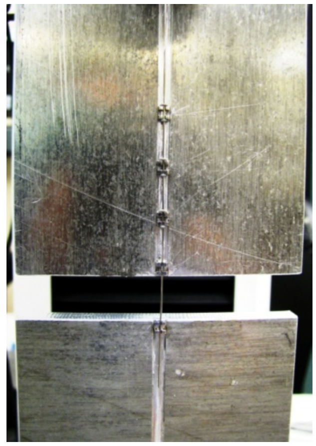

Figure 7. Two custom fixtures with brackets bonded and archwire ligated prior to testing. The bottom plate included the new bracket and test ligature and remained stationary during all tests. The top plate was moved by the Instron machine. The brackets on the top plate were not changed during any of the testing.

The custom metal fixtures allowed a straight wire to be ligated to all five brackets and to be passively centered in all of the bracket slots. The ligatures tested included the low friction experimental ligature from American Orthodontics, conventional ligatures from American Orthodontics (Unistick item #854-279), Sili-Ties™ Silicone Infused Ties from Dentsply GAC International (item #59-950-03; Bohemia, NY), Synergy® Low-Friction Ligatures from Rocky Mountain Orthodontics (item #J0151; Denver, CO), and SuperSlick ligatures from TP Orthodontics, Inc. (item #382-934; La Porte, IN) (Figure 8).

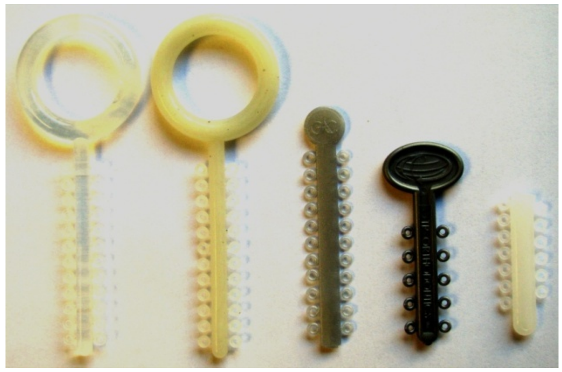

Figure 8. The ligatures tested. From left to right: conventional ligature (AO), low friction test ligature (AO), Sili-Ties (GAC), SuperSlick (TP), Synergy (RMO).

The instrument used to test for friction was a universal testing machine (Instron, Canton, MA) with a 50 Newton load cell and a crosshead speed of 5 mm/min (Figure 9).

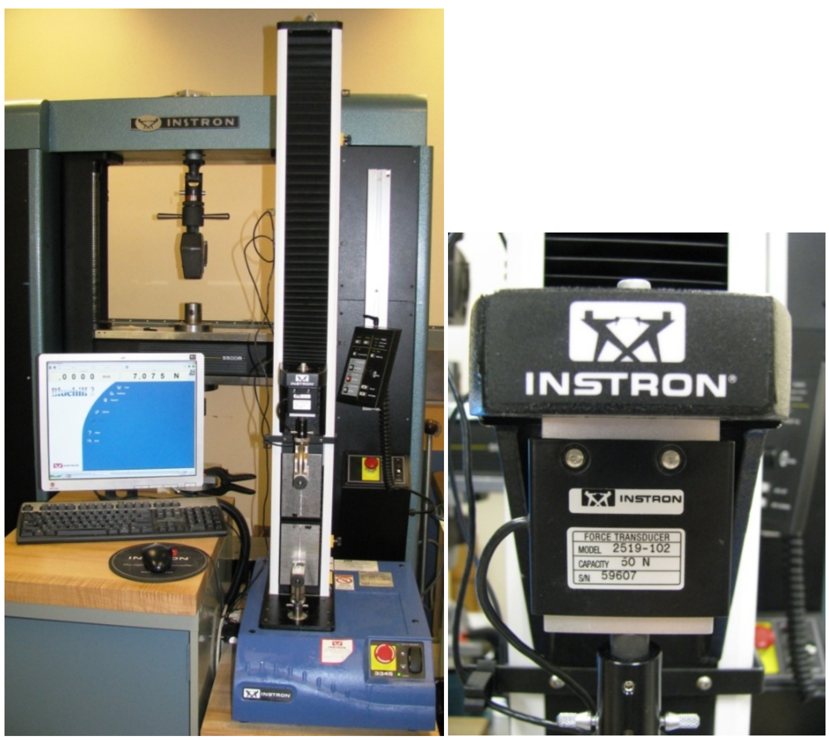

Figure 9. Instron with 50 Newton load cell.

For each test, a new bracket was bonded with ClearFil or All-Bond 2 and light cured for 60 seconds. A test run was completed each time to ensure the new bracket was bonded passively in line with the others. This was important because the reported frictional resistance included not only the friction from the ligature but also any friction from the wire binding on the bracket if it was not bonded passively. A new wire was tied in to the four brackets on the top plate with conventional ligatures and the bracket on the bottom moving plate was left un-tied. The universal testing machine was started and allowed to move the wire for 1 mm. If the measured load was less than 1 gram, the system was considered to be passive and the plates were returned to the starting position of 10.5 mm apart (Figure 10).

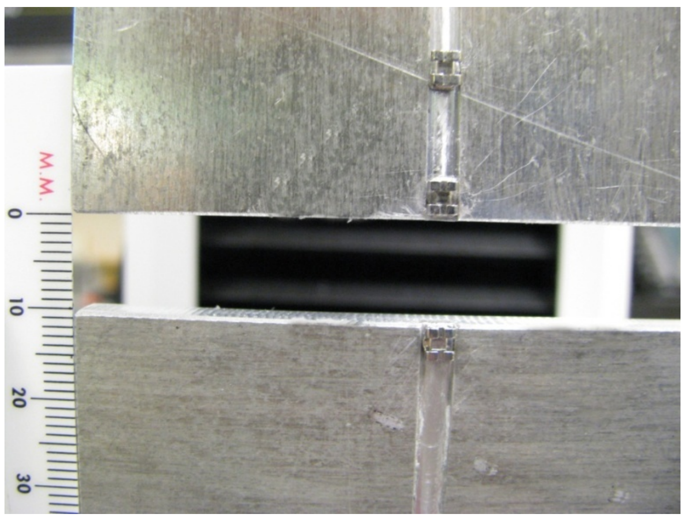

Figure 10. Prior to each test, the plates were returned to a position 10.5 mm apart.

If the load was higher than this, the plates were readjusted and aligned to one another or a new bracket was bonded until the system was once again passive. The ligature to be tested was then tied in to the bottom bracket.

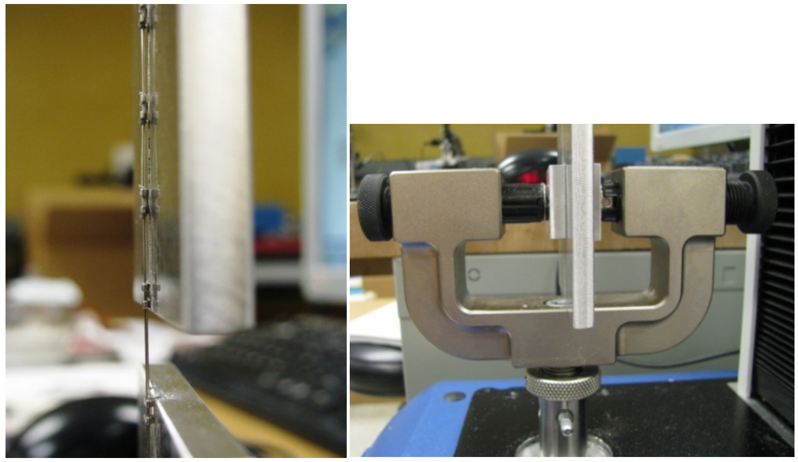

Figure 11. On the left, examining the brackets and plates prior to test to ensure a passive system. If the bottom test plate had shifted, the photo on the right indicates how its position could be altered with the adjustment knobs.

The initial resistance to sliding (static) was determined by the peak force needed to initiate movement and the kinetic resistance to sliding was taken as the force at 5 mm of wire/bracket sliding. Fifteen unique tests were run for each of the five ligature groups. Each test used a new ligature, wire and bracket on the bottom stationary plate. The four brackets mounted to the non-stationary plate were not changed during the course of testing, as the wire was not sliding through any of these bracket slots. Measurements were conducted under dry conditions at room temperature. Following the dry tests, the same protocol was followed to test fifteen of each of the five different ligatures after being soaked in human saliva for twenty-four hours. Immediately prior to testing, each ligature was removed from saliva, ligated to the mounted bracket and one drop of saliva was applied to the ligature immediately before testing (Figure 12).

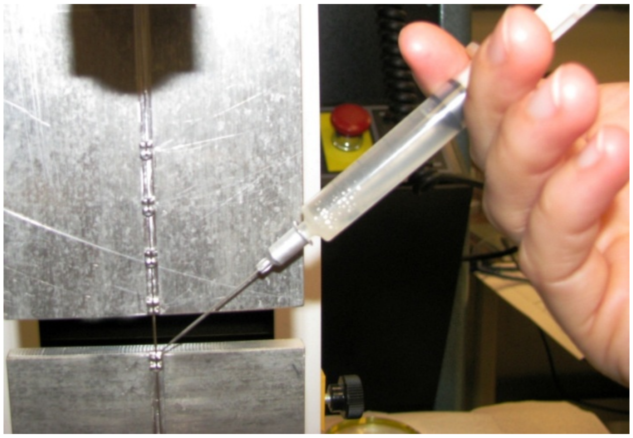

Figure 12. Application of human saliva to the ligature prior to testing.

The friction values were analyzed with statistical software (SPSS Statistics 17.0; SPSS, Inc., Chicago, IL) using two-way analysis of variance (ANOVA) with ligature brand and testing condition (dry or wet) as factors. Significance was set at $\alpha = 0.05$.

RESULTS

Figure 13 illustrates a typical plot of force versus distance when the friction measuring setup was passive. The wire moving along the slot of the un-tied bracket measured less than 1 gram of force or resistance.

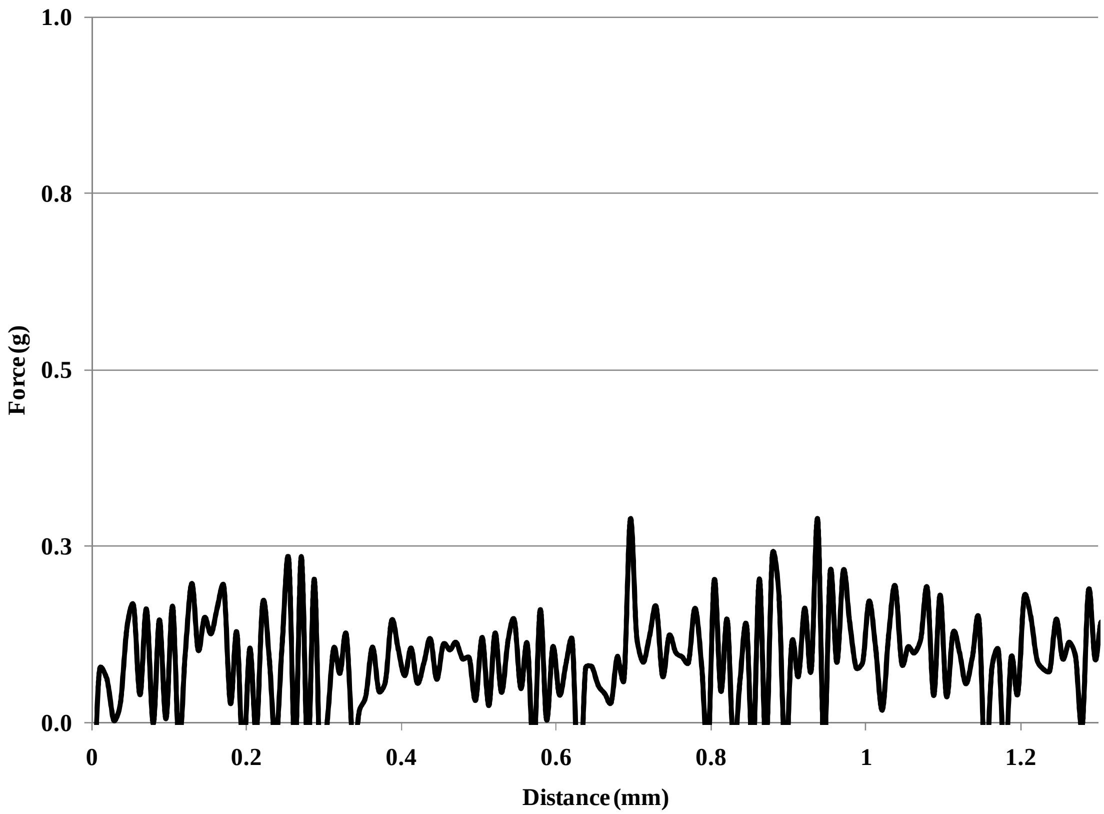

Figure 13. Measured load when a wire was passively moved through the slot of a bracket

With a passive system ensured, the wire was tied into the bracket on the bottom plate and the friction force was measured for 7 mm. A typical plot is shown in Figure 14 with the force values associated with static and kinetic (at 5 mm) friction illustrated in Figure 15.

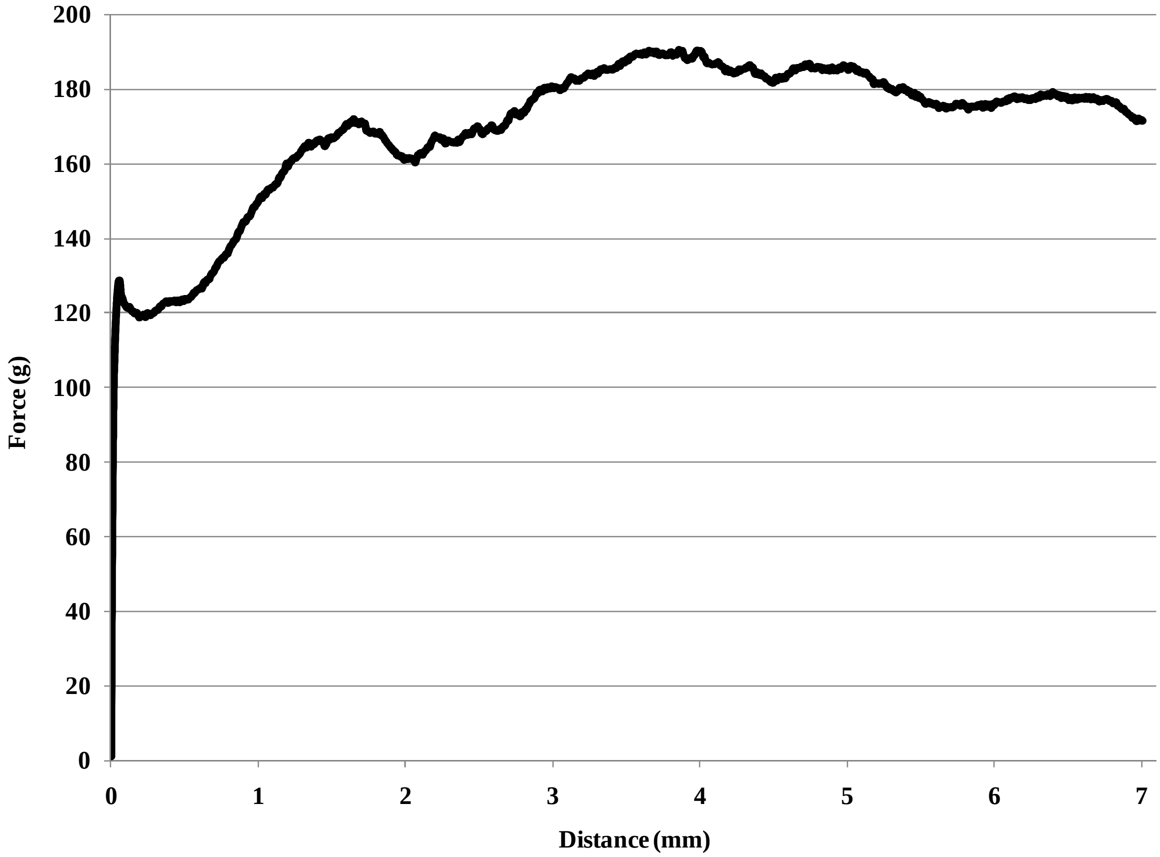

Figure 14. Typical friction plot of force versus distance for an experimental run.

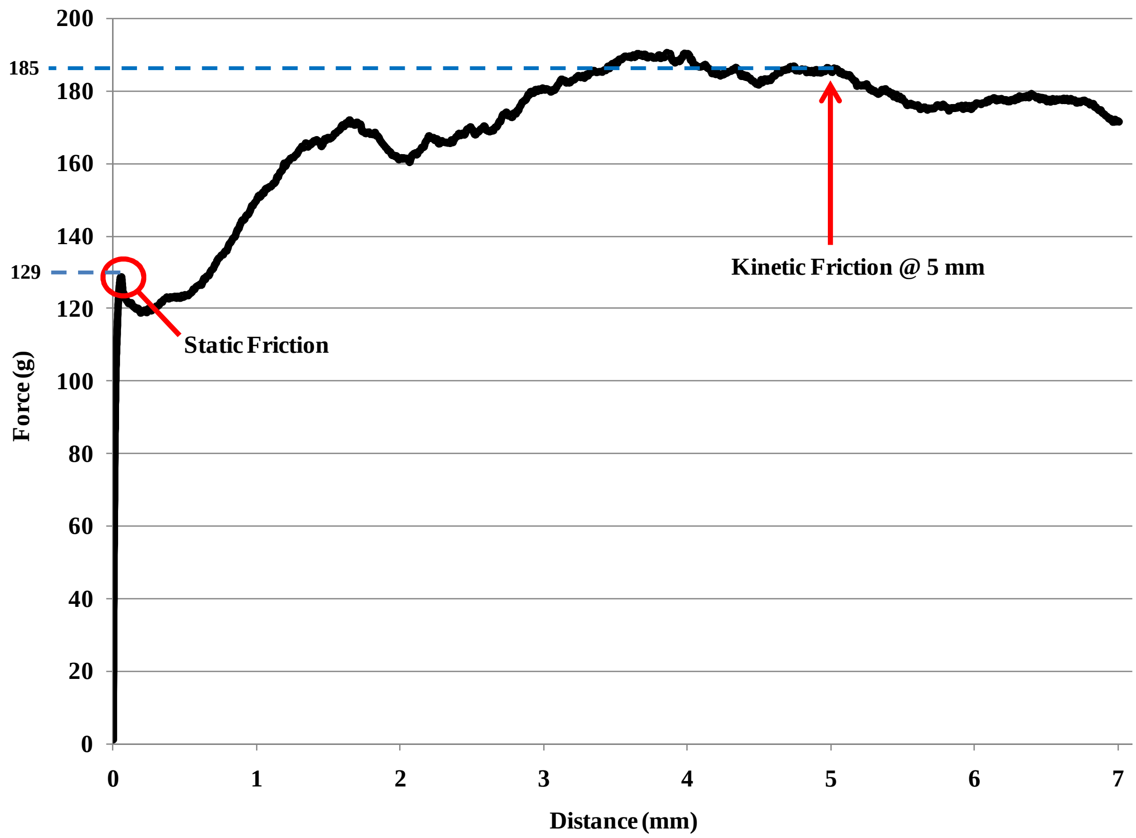

Figure 15. Typical friction plot with indicated areas of static and kinetic (at 5 mm) friction

The mean and standard deviation values for static and kinetic friction for all 5 ligatures tested in both dry and wet conditions are displayed in Table 1. Graphical displays of these mean values are shown in figures 16 and 17. A two way ANOVA was completed with the two factors being ligature brand and condition (wet or dry). This showed a significant interaction between the factors ($p<0.001$) for both the static and kinetic data. Based on this finding, a one way ANOVA was performed to separate the wet and dry conditions. There was a significant difference between the ligatures in both static and kinetic friction under dry and wet conditions ($p<0.001$). A post hoc Tukey test was then done to compare each type of ligature with respect to the others. Tables 2 and 3 display the significance values associated with these comparisons for the dry and wet conditions, respectively. In the dry condition, TP's SuperSlick ligature had significantly ($p<0.05$) greater static friction than all of the other ligatures. SuperSlick also demonstrated significantly ($p<0.05$) more kinetic friction than the AO conventional, AO experimental and Synergy ligatures in the dry condition. In the wet condition, SuperSlick and the AO experimental ligature demonstrated the least static friction, followed by the AO conventional and Sili-Ties ($p<0.05$). The most static friction was seen with the Synergy ligatures. In the wet condition, the SuperSlick, AO experimental and AO conventional exhibited less kinetic friction than the Sili-Ties and the Synergy ligature ($p<0.05$).

Ligature	Dry		Saliva Soaked	
	Static	Kinetic	Static	Kinetic
AO Conv	111.8 ±29.6, A	158.6 ±52.3, A	69.1 ±17.4, B	83.6 ±21.2, A
AO Exp	101.4 ±28.0, A	134.1 ±36.8, A	53.8 ±10.5, A	74.2 ±18.4, A
Sili-Ties™	124.2 ±32.2, A	177.6 ±43.1, B	73.7 ±13.4, B,C	112.9 ±19.5, B
Synergy®	105.6 ±24.1, A	157.9 ±62.2, A	86.8 ±14.1, C	113.9 ±23.2, B
SuperSlick	153.1 ±23.6, B	210.4 ±48.7, B	46.6 ±14.1, A	80.1 ±14.2, A

Table 1: Mean and standard deviation values for static and kinetic friction for all five ligatures in the dry and wet conditions

Ligature Comparison		Kinetic P Value	Static P Value
AO Conv	AO Exp	.654	.842
	Sili-Ties	.831	.739
	Synergy	1.00	.973
	SuperSlick	.041	.001
AO Exp	Sili-Ties	.124	.174
	Synergy	.679	.994
	SuperSlick	.001	.000
Sili-Ties	Synergy	.811	.363
	SuperSlick	.368	.042
Synergy	SuperSlick	.037	.000

Table 2: Significance values for all five ligatures in the dry condition

Ligature Comparison		Kinetic P Value	Static P Value
AO Conv	AO Exp	.675	.033
	Sili-Ties	.001	.898
	Synergy	.001	.008
	SuperSlick	.988	.000
AO Exp	Sili-Ties	.000	.002
	Synergy	.000	.000
	SuperSlick	.917	.624
Sili-Ties	Synergy	1.00	.090
	SuperSlick	.000	.000
Synergy	SuperSlick	.000	.000

Table 3: Significance values for all five ligatures in the wet condition

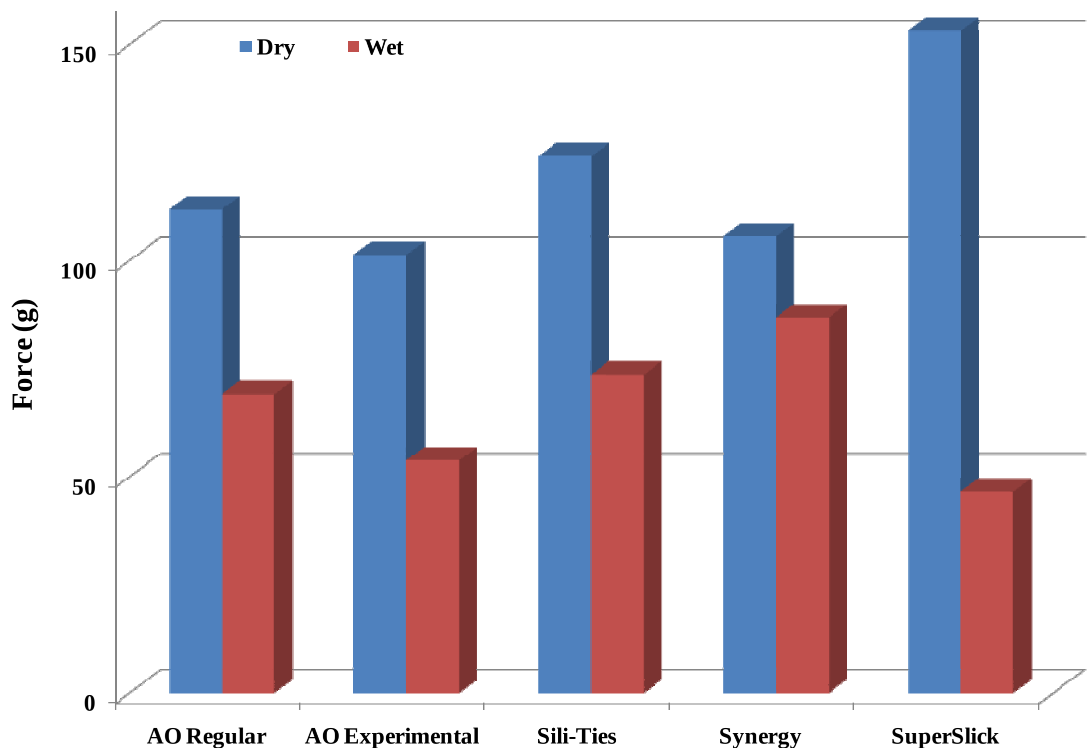

Figure 16. Static friction values for all 5 ligatures in the dry and wet conditions

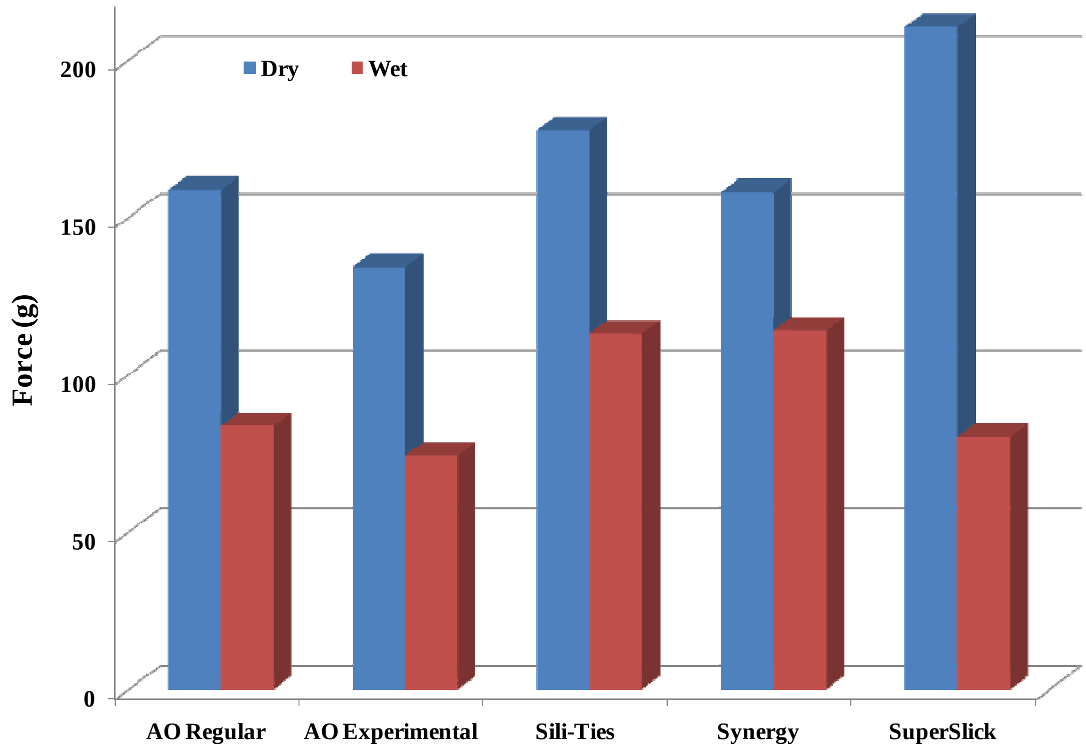

Figure 17. Kinetic friction values for all 5 ligatures in the dry and wet conditions

DISCUSSION

The brackets in this study were chosen to be with zero degrees of tip and torque to allow the only friction present to be classical friction and not due to binding or notching. Similarly, the wire and bracket were kept constant in terms of material and size to allow the ligature to be the only variable among the three components. The crosshead speed of 5mm/min was based on the work of Kusy et al.[43] who found that as sliding velocity decreased from 10 mm per minute to $0.5x10^{-3}$ mm per minute, the coefficient of friction for stainless steel surfaces was relatively unaffected. A new ligature was used for each individual test; however Hain et al.[34] demonstrated that repeating the test run 5 times with the same ligature made no statistical difference in friction. However, each test run was done 15 times in this study, so in an effort to be as accurate as possible, a new ligature was used each time.

This study indicates that with all of the ligatures in both the static and kinetic conditions, friction was reduced in the wet conditions relative to the dry. This finding is consistent with the results from several studies including Hain et al.[34], who found that regular, uncoated ligatures showed a significant reduction in friction after one week of saliva exposure compared to sixty minutes of saliva exposure, while coated ligatures (SuperSlick) were not affected. However, when comparing SuperSlick ligatures that have been soaked in saliva for 60 minutes, they showed significantly less friction than those that have been given just one drop of saliva prior to testing. This indicates that after just one hour of saliva exposure, SuperSlick demonstrates less friction and this lowered level is maintained at least one week. Khambay[35] did not find that SuperSlick demonstrated lower levels of friction compared to conventional and stainless steel ligatures, however the ligatures were dropped with saliva during testing and were not soaked for any length of time. This further supports that the presence of saliva is a necessary component to making these ligatures perform correctly.

The manufacturing process and composition of the low friction ligatures varies amongst the different brands. While American Orthodontics is unable to disclose the composition of their new low friction ligature, it is known that it is injection molded. According to the company, small pellets are poured into a funnel shaped container with a screw (auger) running down the center. As the pellets are heated, they liquefy and follow the threads of the screw (auger) down and as it turns are forced through the funnel opening into the mold. The material is then cooled and extracted from the molds.

SuperSlick, a ligature made by TP Orthodontics, is created with a hydrophilic coating so that when wetted by saliva the surface becomes slippery.[44] It is an injected molded polyurethane ligature dipped for 2.5 minutes in a hydrophillic polymer blend of methylene chloride (600 grams), methyl ethyl ketone (400 grams) and polyvinylpyrrolidone (10 grams).[44] This coating is then cured by air drying for 10 minutes and oven baking at 80° C for 20 minutes.[44] According to the manufacturer, Sili-Ties (GAC), are injected with a silicone additive that is time released during the life of the product in the mouth.

The Synergy bracket was introduced to the market in the 1990's featuring a traditional bracket design with six tie wings and rounded slot walls and floors. According to the manufacturer, this rounding reduces friction between the wire and the slot and increases the inter-bracket span. The six tie wings allow a variety of ligature configurations, including tying only the middle two wings to allow minimal contact of the ligature against the wire. More recently, removable covers were added to posterior and canine brackets, mimicking a buccal tube scenario to further reduce the friction in the preliminary stages of treatment. The Synergy low friction ligature (Rocky Mountain Orthodontics) is silicone injected and is intended to be used in conjunction with their Synergy R bracket. In 2003, Redlich et al.[45] demonstrated that the Synergy bracket with a conventional ligature (Sani-Ties, GAC International) ligated to the middle pair wings produced similar amounts of static and kinetic friction to the control group (Omni Arch twin brackets by GAC International) at 0°, 5°, and 10° wire-bracket angulations. However, since this study the bracket design has been altered and the low friction ligature has been introduced. More recently, in 2009, Franchi et al.[39] determined that the Synergy R bracket with the Synergy low-friction ligatures as well as conventional brackets tied with the Synergy low-friction ligatures produced forces for tooth movement that were similar to those generated by self-ligating brackets. However, the difference between these systems and conventional ligatures was only seen at tooth displacements greater than 3.0 mm. In 2010, Stefanos et al.[46] compared six bracket systems and found the mean static friction of the Synergy R bracket (23.8 g) to be lower than SmartClip (30.3 g), In-Ovation C (33.4 g), In-Ovation R (38.1 g) and Speed (83.1 g) and higher than only Damon 3 MX (8.6 g). It was not indicated if the Synergy R bracket was ligated or if the cover was on the bracket. Due to the wide variation in bracket design, type and method of ligation and testing parameters, comparisons between this study and the previous studies cannot be made regarding the Synergy ligature.

The question then becomes, since these elastomeric ties have been shown to decrease friction in the laboratory setting, does this translate to less friction clinically and if it does, does this decrease in friction increase treatment efficiency? Franchi et al. produced the only in vivo study on low-friction ligatures.[47] The aim of the study was to evaluate the changes in the transverse dimension of the maxillary arch produced by the Slide ligature during the leveling and aligning stage of treatment in 20 nonextraction patients. They found statistically significant increases in the transverse dentoalveolar width and the perimeter of the maxillary arch. However, these changes were not compared with matched controls and no study has ever duplicated these findings. The best evidence regarding the effect the ligator has on friction involves 2 systematic reviews of in vivo studies with self-ligating brackets. Chen et al. published a meta-analysis on self-ligating brackets including 16 in-vivo studies (2 randomized controlled trials, 10 cohort studies and 4 cross-sectional studies).[48] Only 4 of these were considered to have a low risk of bias and 7 qualified for the meta-analysis. Three retrospective cohort studies with a moderate risk of bias indicated that self-ligating brackets do not decrease total treatment time.[49-51] Five studies (2 randomized controlled trials and 3 prospective cohort studies) indicated there was no significant difference between conventional and self-ligating brackets in the efficiency of aligning the mandibular anterior incisors.[52-56] One prospective cohort study indicated there was no significant difference in the rate of en-masse space closure between conventional and self-ligating brackets.[57] While this tends to indicate treatment is no more efficient with a decrease in friction from the ligator, the authors emphasize the quantity and quality of evidence is still poor and more randomized controlled trials are necessary. In the same year, Fleming and Johal also published a systematic review on the topic including similar studies and they also concluded that “there’s insufficient evidence to support the use of self-ligating fixed orthodontic appliances over conventional appliance systems or vice versa.”[58]

Future studies on the topic should include randomized clinical controlled trials comparing the rate of mandibular anterior alignment or space closure with low friction ligatures compared with conventional ligatures. In the absence of sufficient evidence, it is acceptable to use low friction ligatures in lieu of conventional ligatures because they offer few disadvantages. While they may or may not decrease treatment time or clinical levels of friction, there is no increased cost or alteration in clinical practices associated with them such as with self-ligating brackets.

CONCLUSIONS

- In the dry condition, the SuperSlick ligature demonstrated more static friction than all of the other ligatures.
- In the dry condition, SuperSlick demonstrated more kinetic friction than the AO conventional, AO experimental and Synergy ligatures.
- In the wet condition, SuperSlick and the AO experimental ligature demonstrated the least static friction, followed by the AO conventional and Sili-Ties. The most static friction was seen with the Sili-Ties and Synergy ligatures.
- In the wet condition, the SuperSlick, AO experimental and AO conventional exhibited less kinetic friction than the Sili-Ties and the Synergy ligatures.
- Due to the design of this study, no conclusions may be drawn as to the clinical performance of low friction ligatures.
- Future studies should include randomized clinical controlled trials comparing low friction ligatures with conventional ligatures in regards to treatment time and efficiency.

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