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# Comparison of Resistance to Sliding between Brackets and Archwires Utilizing Various Ligature Materials

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# COMPARISON OF RESISTANCE TO SLIDING BETWEEN BRACKETS AND ARCHWIRES UTILIZING VARIOUS LIGATURE MATERIALS

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A Thesis Presented to the Faculty of the College of Dental Medicine of

Nova Southeastern University in Partial Fulfillment of the Requirements for the Degree

of

MASTER OF SCIENCE

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**I certify that I am the sole author of this thesis, and that any assistance I received in its preparation has been fully acknowledged and disclosed in the thesis. I have cited any sources from which I used ideas, data, or words, and labeled as quotations any directly quoted phrases or passages, as well as providing proper documentation and citations. This thesis was prepared by me, specifically for the M.Sc.D. degree and for this assignment.**

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# Abstract

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DEGREE DATE: DECEMBER 16, 2016

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**Objectives:** The purpose of this study was to investigate the association between ligature material and frictional force created during orthodontic cuspid retraction. Maximum static and mean kinetic frictional resistance between conventional metallic orthodontic appliances and esthetic orthodontic appliances will be compared as well. **Background:** The use of ceramic brackets in conjunction with coated archwires and ligatures as an alternative to conventional stainless steel appliances has increased in response to the demand for more esthetic orthodontic appliances. Esthetic appliances are associated with increased frictional forces and therefore thought to slow the orthodontic treatment. Knowledge of frictional forces generated within various orthodontic appliances is necessary so that appropriate forces can be delivered to achieve clinically desirable rate of tooth movement during sliding mechanics. Frictional forces at the bracket-archwire-ligature interface can affect sliding mechanics. **Methods**: In order to measure and compare frictional forces at the bracket-archwire-ligature interface, four maxillary premolar brackets were mounted on a Plexiglass acrylic sheet and one movable bracket was attached to the center of the archwire span. Two types of brackets were used: stainless steel (SS) and ceramic. Brackets used were 0.022 x 0.028 inch slot with RT prescription (DENTSPLY GAC). Tests were performed with 0.017x0.025" SS and 0.017x0.025" Epoxy-coated SS archwires on a Universal Testing Machine (Instron, Grove City, PA) at a crosshead speed of 2.5mm/min, as used by Khamatkar et al[2]. Archwires were ligated to brackets using 0.010" stainless steel, 0.010" Teflon-coated stainless steel and elastomeric ligatures. The movable bracket was fitted with a 10mm long, 0.045" thick stainless steel arm. A 100gm weight was suspended from the arm to represent the force acting at the center of resistance. Mean kinetic friction was measured for 120 seconds at ten second intervals, beginning at the 30-second time point. Maximum static and kinetic friction measurements were repeated six times and the mean was calculated for each bracket, archwire and ligature combination. **Results:** Elastomeric ligatures produced more frictional forces than stainless steel ligatures. Teflon-coated coated stainless steel ligatures generated the least amount of frictional resistance. The combination of ceramic bracket, epoxy-coated stainless steel archwire and Teflon-coated stainless steel ligature produced frictional forces that were lower than those by stainless steel bracket, stainless steel archwire and stainless steel ligature. **Conclusions:** The ligature material used plays a crucial role in the generation of frictional forces at the bracket-archwire interface. Ceramic brackets are comparable to stainless steel brackets in the amount of frictional forces produced. However, the epoxy-coated stainless steel archwires are not as efficient due to the lack of durability of the surface coating.

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# Chapter 1: INTRODUCTION

Orthodontic tooth movement is dependent on controlled mechanical forces to stimulate biological responses within the periodontium.[1] When force is applied for tooth movement, part of it is dissipated as friction, and the remainder is transferred to the supporting structures of the tooth to mediate tooth movement. Hence, it is necessary that the applied force be of sufficient magnitude to overcome friction and at the same time lie within the optimum range of force necessary for tooth movement.[2] There are various techniques to achieve tooth movement, but the most common includes an edgewise bracket that slides along a continuous archwire.[1]

The use of ceramic brackets in conjunction with coated archwires and ligatures as an alternative to conventional metallic appliances has increased in response to the demand for more esthetic orthodontic appliances.[3] Esthetic appliances are associated with increased frictional forces and therefore thought to slow orthodontic treatment.[4] Previous studies have shown that the material properties of brackets, archwires, and ligation materials play a significant role in the generation of friction.[1,2,5,6] The magnitudes of frictional forces, apart from physical variables, are also affected by biological variables.[4] The biological variables that can have an effect on friction are the presence of saliva and the functions of the oral environment.[7-9] The physical variables affecting frictional resistance that can be controlled clinically are archwire size and shape, bracket-slot dimensions, relative angulation of the bracket and archwire, inter-bracket distance and ligature material.[4]

Frictional forces at the bracket-archwire-ligature interface can affect sliding mechanics. Therefore, knowledge and consideration of the frictional forces generated within an orthodontic appliance is necessary to determine the proper active-force magnitudes required to achieve a clinically desirable time-rate of tooth movement during sliding mechanics.

### 1.1. Friction

Friction is defined as a force that retards or resists the relative motion of two objects in contact. The direction of action is parallel and opposite to the direction of sliding. Its maximum magnitude is directly proportional to normal force and the constant is called the coefficient of friction. It is described by the equation $F = \mu N$; where F is the magnitude of friction, $\mu$ is the coefficient of friction and N is the magnitude of normal force.[10] The normal force (N) is the force perpendicular to the direction of sliding and the frictional force. It can be seen as the force pushing the two surfaces together.[8] The coefficient of friction ($\mu$) is a constant that describes the relative difficulty of sliding surfaces past each other. Its value is determined by the surface characteristics of the two materials involved. There are two coefficients of friction; a static coefficient when objects are at rest and a kinetic coefficient when two objects are sliding against each other. The static coefficient of friction will always be larger than the corresponding kinetic coefficient of friction. Static frictional force is the smallest amount of force needed to initiate movement between two objects. Kinetic frictional force is the amount of force that inhibits an object from sliding at a constant speed.[10,11]

Leonardo da Vinci conducted the earliest known friction experiments in the 16th century. Amontons and Coulombs later in the 18th and 19th centuries defined the classical laws of friction. The three laws of dry friction are: 1) frictional force is directly proportional to the load; 2) friction is independent of the area of contact between the surfaces; and 3) friction is independent of the sliding velocity.[12]

### 1.2. Friction in Orthodontics

Kusy et al discussed the classical laws of friction in relation to mechanics used in orthodontics. They suggested that certain principles remain true in orthodontics while others do not. The first law that states friction is proportional to the normal force is always obeyed in orthodontics. The second law, the force of friction is independent of the apparent area of contact, is usually followed in orthodontics. But the third law, kinetic friction is independent of the sliding velocity, most often does not hold true during orthodontic tooth movement. This is due to the extremely slow velocity during tooth movement and also that the velocity is always changing.[13]

According to Rossouw et al, it is impossible to differentiate between static and kinetic friction at extremely slow velocity. Objects moving at such slow velocities alternate between extended periods of no movement and periods of rapid movement. Teeth move along an archwire in a similar manner that was described by Rossouw et al as the "stick-slip" phenomenon. The system is loaded elastically until the force within the system overcomes the static force of friction. This is known as the stick part of the cycle. The two objects then slip across each other until the force in the system reduces below the kinetic force of friction and they stick again.[14] This stick-slip phenomenon is thought to play an important role in compromising tooth movement and decreasing efficiency during orthodontic tooth movement. With increased friction, there is decreased efficiency. Efficiency in orthodontics is the amount of force an archwire is able to deliver compared to how much force it actually applies. It has shown to vary between 40% to 88%.[9]

When closing spaces orthodontically, Nanda et al mention that orthodontists usually use two types of methods. First is a frictionless technique, where closing loops are incorporated into an archwire and activating the retraction arches helps close the spaces. The other method is called "sliding mechanics".[11] There are two types of sliding mechanics in orthodontics. A single tooth moving along an archwire is one type. An example of this is cuspid retraction in first bicuspid extraction cases. The other type is when an archwire slides through multiple stationary brackets. An example of this is when an archwire moves distally through the brackets on the posterior teeth during en masse retraction. Sliding mechanics is strongly influenced by friction at the bracket, archwire and ligation interface.[15]

Sliding mechanics also occurs during the first stage of orthodontic treatment when teeth are being aligned with the help of light, flexible archwires. These wires have the ability to engage misaligned teeth and move them into alignment as the wire springs back into its passive form.[16] A longer length of wire is needed to engage misaligned teeth. As the teeth are aligned, there is a decrease in the total distance between brackets in the arch. The excess wire slides distally through the brackets to extend beyond the most distal bracket.[17]

A great deal of research has been conducted to understand the role of friction and how it can be minimized. Different variables have been identified that contribute a significant amount of friction during orthodontic treatment. These variables can be divided into two categories: biological and physical.[11]

## 1.3. Variables Affecting Friction

### 1.3.1. Biological Variables

#### 1.3.1.1. Saliva

Multiple *in vitro* studies to evaluate friction are conducted under dry conditions. This does not allow to us replicate the oral environment. The orthodontic appliance is continuously being bathed by saliva, plaque and food particles intra-orally. Therefore, to address this issue, some studies have been carried out to assess the effect of human or artificial saliva on friction.

Kusy et al conducted a study to test the effects of different lubricants on friction. They used water, human saliva and five types of artificial saliva. Tests run with human saliva showed the least amount of frictional coefficient. Results of tests run using water and in dry state were similar. The groups utilizing artificial saliva had the highest amount of friction.[18] In another study, Kusy et al reported that stainless steel wires had greater frictional resistance in the wet state compared to the dry state. Whereas the beta-titanium wires had lower frictional resistance in the wet state compared to the dry state.[19]

Baker et al found that there was no significant reduction in friction with artificial saliva but human saliva significantly reduced the static friction.[8] Stannard et al carried out a test to assess kinetic friction of archwires made up of different alloys. They reported that although the artificial saliva had no effect on Teflon and cobalt chromium wires, it significantly increased the kinetic friction for stainless steel, nickel titanium and beta-titanium wires.[20]

These are just some of the studies that have shown that artificial saliva is a poor lubricant for *in vitro* friction studies. Studies utilizing human saliva to test their effect on friction have shown conflicting evidence when used as a lubricant.

#### 1.3.1.2. Oral Forces

A variable that likely plays a role in orthodontic friction is the force of occlusion.[9] Periodontal ligament surrounding the teeth allows for some movement and the alveolar bone can bend in response to function as well as orthodontic forces.[21] During speaking, chewing and swallowing, teeth come in contact against each other thousands of times a day. Therefore it is expected that the teeth and orthodontic appliances are moving in relation to one another.

Various studies have included perturbations in their methodology to replicate the oral environment. Braun et al found that every time either the bracket or wire was tapped, the frictional force characteristically dropped to zero.[9] Bunkall et al reported that the maximum static and mean kinetic friction was reduced by 35%-70% once perturbations were added.[22] According to Iwasaki et al, who conducted an *in vivo* study to assess the effects of chewing gum on frictional resistance, masticatory forces reduced frictional resistance, but they were unpredictable and inconsistent. They also stated that the frictional resistance was reduced under oral forces when brackets were ligated with stainless steel ligatures as opposed to elastomeric ligatures. They suggested that masticatory forces cannot eliminate frictional forces and that ligation method had a similar effect as intra-oral vibration.[6]

### 1.3.2. Physical Variables

#### 1.3.2.1. Brackets

**Bracket Material**

The most popular bracket material used in orthodontics is stainless steel. Due to a higher number of adults seeking orthodontic treatment, need for esthetic appliances have increased. To meet this demand, manufacturers have been developing brackets of different materials that are more esthetic.

Numerous studies to assess frictional characteristics of bracket materials have shown that the stainless steel brackets tend to generate less frictional resistance than their ceramic counterparts.[19,23-25] Pratten et al suggested that the greater friction in ceramic brackets might be due to greater surface roughness.[24] But there are other studies that have revealed that ceramic brackets show similar or even lower frictional resistance than the stainless steel brackets.[7,26,27] Kusy et al compared stainless steel brackets with polycrystalline alumina brackets and reported that there was no difference in frictional resistance between the two.[7] Omana et al reported a similar result and suggested that the reduced friction values in certain ceramic brackets might be due to the injection-molding manufacturing process, which produces very smooth surfaces.[27]

**Slot Size**

Studies organized to assess the difference in frictional resistance between the two slot sizes with occluso-gingival heights of 0.018” and 0.022” have shown that there is no significant difference in the amount of friction produced.[28] In spite of this, Kusy et al suggest that the slot height does affect the critical contact angle. Critical contact angle is achieved when the wire makes contact with opposite ends of the bracket slot (Figure 1). As the bracket tips under increased forces, the archwire binds and then notches, which increases the frictional resistance. For this reason, they recommend the practitioner to be more precise in initial leveling and aligning while using a 0.018” slot as they might encounter increased binding.[29]

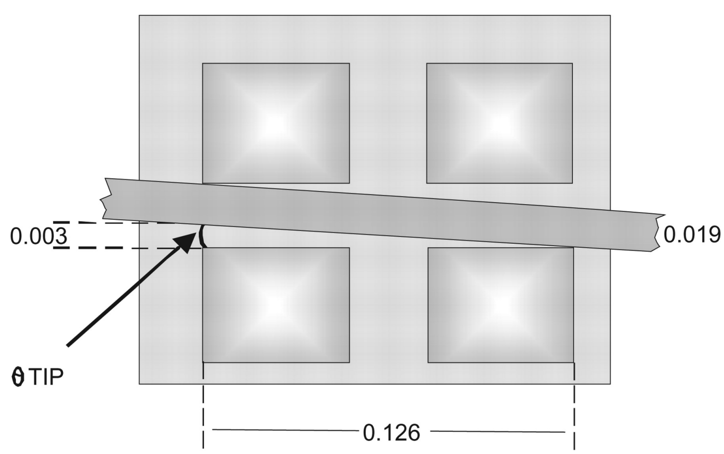


**Figure 1 Schematic representation of critical angle**

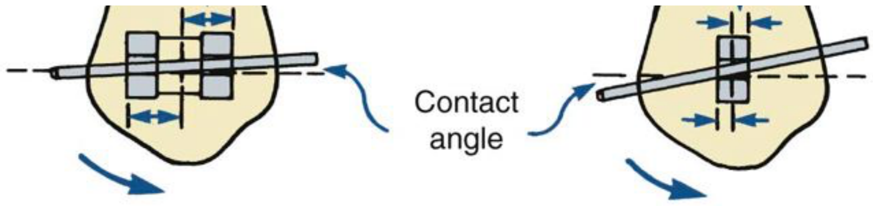


**Figure 2. Contact angle with respect to bracket width**

**Bracket width**

Critical contact angle is also affected by the bracket width. Wider brackets do not allow for higher angulations compared to their narrower counterparts (Figure 2). Frank et al conducted a study to test the effect of brackets with varying widths on frictional resistance. They concluded that as the bracket width increased, so did the amount of friction.[15] On the other hand, Drescher et al found that the opposite was true. They suggested that while the bracket width can affect friction, the material of the archwire played a larger role.[17] Kapila et al also concluded that frictional resistance was higher with wider brackets and they implied that the elastomeric ligature had to be stretched more to fit the wider brackets, which in turn increased the force of ligation and hence the amount of friction.[30]

**1.3.2.2. Ligation**

The method of ligation is another factor that plays a role in the generation of friction along with the bracket and archwire. There are different types of ligation materials available in the market, but the most commonly used are the elastomeric and stainless steel ligatures.[31] Multiple studies have evaluated the difference in frictional resistance between stainless steel ligatures and elastomeric ligatures. Frank et al found that at similar ligation force, the difference in the amount of friction produced was not significant. But as the amount of ligation force increased, so did the frictional resistance.[15]

In another study, Khambay et al used different kinds of elastomeric ligatures and compared them with their stainless steel counterparts to evaluate frictional resistance. They found that although the stainless steel ligatures had the highest amount of ligation force, they produced the least amount of frictional resistance. Whereas the elastomeric ligatures of different kinds had significantly different frictional resistance values, but they did not correspond with the ligation force levels.[32]

Various other studies in the literature have shown that stainless steel ligatures produce less frictional resistance than elastomeric ligatures, but there is a large variation in the amount of friction produced by elastomeric ligatures of different size and shape.[1,33,34]

With gaining popularity of esthetic appliances, another type of ligature that is available is a coated stainless steel ligature. The most commonly used is a Teflon-coated ligature. They can be used as an esthetic option in conjunction with ceramic brackets. Edwards et al assessed the difference in the amounts of friction produced by elastomeric, stainless steel and Teflon-coated ligatures using stainless steel brackets and archwires. They found that Teflon-coated ligatures produced the lowest friction. The elastomeric ligatures tied in a figure eight pattern produced more friction than both elastomeric ligatures that were conventionally tied and stainless steel ligatures.[35]

De Franco et al also found that Teflon-coated stainless steel ligatures had lower mean static friction values than the elastomeric ligatures. The Teflon-coated ligatures produced less friction regardless of bracket type (monocrystalline or polycrystalline), archwire type (stainless steel or nickel-titanium) or bracket/archwire angulation (5,10 or 15 degrees). They suggested that the lower frictional resistance was due to the lower coefficient of friction of the Teflon material compared to the elastomeric ligatures.[1]

Although, orthodontists more commonly use elastomeric ligatures, it has been shown that stainless steel ligatures are superior to their elastomeric counterparts in most aspects. The reason elastomeric ligatures are used more commonly is due to reduced patient chair time.[36] Shivapuja et al have shown that using wire ligatures adds almost twelve minutes to the time needed to remove and replace two archwires.[37]

#### 1.3.2.3. Archwires

**Size**

As the size of the wire increases, it fills more of the slot, increasing the tendency of friction to rise. On the contrary, smaller sized wires have more space in the slot and are also more elastic, which helps in reducing the amount of friction produced.[13,15,17,33,38]

Kusy et al reported that frictional resistance is higher in larger wires because as the diameter of the wires increases, free space in the slot diminishes and the critical angle is met with less tipping of the bracket. Larger wires also have more stiffness and more likely to cause notching of the wire. Binding occurs as the slot permanently deforms the surface of the archwire. At this point, sliding of the archwire against the bracket comes to a halt and binding overshadows other factors influencing friction.[39]

**Shape**

Orthodontic archwires are available in two shapes; round and rectangular. Various studies have reported that round wires produce less friction than rectangular wires, but there are other factors that play a role as well.[15,17,38,40]

Frank et al reported that 0.020” round stainless steel wire displayed higher frictional resistance than larger 0.017 x 0.025” and 0.019 x 0.025” rectangular stainless steel wires. They suspected that the round wire experiences higher pressure as compared with the rectangular wire as it makes a point contact with the slot, whereas the rectangular wire makes broader contacts. This would lead to increased notching of the round wire and hence increased resistance to sliding.[15]

Drescher et al found that a 0.016” round stainless steel wire produced the same frictional resistance as a 0.016 x 0.022 stainless steel wire. They concluded that the most important factor influencing friction was the occluso-gingival dimension of the wire.[17]

**Composition**

There are different types of archwires that are now available to the orthodontist. The most extensively used are the stainless steel archwires. Over the past few decades, the introduction of other metal alloys has made a striking difference in orthodontic mechanics. Stainless steel wires are strong, formable and can be soldered, but have low flexibility. The newer super-elastic alloys such as nickel-titanium and beta-titanium alloys are a lot less stiff than the stainless steel wires.  Because these archwires are made up of different materials, they have varying coefficients of friction.[13]

Various studies have been conducted to assess the frictional resistance differences between wires of different materials and it has been found that beta-titanium wires show the highest amount of friction generated followed by nickel-titanium, cobalt-chromium and stainless steel. The authors have speculated that titanium alloys with increased surface roughness might be the reason for increased frictional resistance.[7,15,17,28,30,41]

The above however is true for brackets that are well aligned with the archwire. Frank et al reported that with increased angulation of the bracket, nickel-titanium wire has less frictional resistance than stainless steel or cobalt-chromium wires. They indicate that since the Young's modulus of elasticity of nickel-titanium is one-sixth that of the other two metals, the increased elasticity reduces the force at the contact angle, thereby reducing the amount of friction.[15]

**Surface Characteristics**

The second law of dry friction states that the force of friction is independent of the surface area of contact. In spite of this, many believe that rougher surfaces are the cause of increased friction.[13,15]

Kusy et al used a laser spectroscopy to identify surface roughness of different alloys. They found that nickel-titanium wires have the roughest surface, followed by beta-titanium and cobalt-chromium, and the smoothest surface was of stainless steel archwires.[42] All wires were drawn across stainless steel surfaces with varying roughness. They reported that surface roughness had little effect on the coefficient of friction and hence a clear relationship does not exist between surface roughness and coefficient of friction.[43]

Prososki et al also conducted a study to measure the surface roughness and frictional resistance of twelve different types of wires. They also reported that the stainless steel wire was the smoothest followed by beta-titanium and nickel-titanium. There was no significant correlation between surface roughness and frictional resistance.[44]

Proffit states that the surface chemistry, and not surface roughness, is the major factor affecting frictional characteristics of an archwire. When the titanium content of a wire is increased, its reactivity or ability to form metal to metal bonds increases.[45] Kusy et al report that a beta-titanium wire has shown enough reactivity to cold-weld itself to a stainless steel bracket, which would make sliding impossible.[43]

**Surface Characteristics of Esthetic Archwires**

With advances in ceramic brackets, esthetic wires are also getting a lot of attention from the manufacturers. These esthetic wires can be separated into two categories: transparent non-metallic and coated metallic.[46]

Transparent non-metallic or composite archwires can be composed of ceramic fibers that are either embedded in a linear or cross-linked poly-metric matrix. These wires vary in stiffness from that of a flaccid multi-stranded archwire, to nearly that of a beta-titanium archwire.

Majority of the esthetic archwires available today are stainless steel or nickel-titanium wires with an esthetic coating applied via ion implantation. Epoxy resin, Teflon, rhodium and palladium are the commonly used materials to coat archwires. Ion implantation is a process in which a substrate is refined by ionized atoms, adhering to the high-energy, positively charged radicals of the coating material through negative loading. The radicals penetrate the substrate surface and bind with the substrate. Therefore, it permanently modifies the surface of the archwire.

Husmann et al reported that ion implantation fills in the rough areas with the coating material at microscopic level, which smoothens the surface and could possibly decrease frictional resistance. This process can also increase the stiffness and reduce resiliency.[47] Elayyan et al have shown that the esthetic coating is not durable and there is fragmentation of the coating, which not only reduces the esthetic benefit, but can also increase the frictional resistance.[48]

As described earlier, although beta-titanium wires have a smoother surface compared to nickel-titanium, it produces more frictional resistance. Therefore, it should not be assumed that a smoother appearing archwire would generate less amount of friction.

### 1.4. Importance of the Study

Frictional forces at the bracket-archwire-ligature interface can affect sliding mechanics.[49] Studies comparing ceramic and stainless steel brackets have shown the coefficient of friction and frictional resistance with ceramic brackets to be greater.[7,19] Additionally, prior research has shown that certain coated wires can reduce frictional losses when compared to uncoated wires, although no correlation between surface roughness and frictional forces of the wires was reported.[47]

Iwasaki et al, calculated that 31 to 54% of the total frictional force generated by a premolar bracket that slides along a 0.019 × 0.025 inch SS archwire was due to the force of ligation.[6] Similarly, a study by Schumacher et al found that friction was determined mainly by the type and force of ligation.[5] In fact, De Franco et al reported that Teflon-coated ligatures produced less frictional resistance than elastomeric ligatures.[1]

Orthodontic literature contains considerable documentation on the effects of different variables on friction. Studies have evaluated and compared frictional forces generated at the interface of metallic and ceramic brackets, coated and uncoated wires, and coated and uncoated ligatures in different combinations. To our knowledge, no study has yet compared the frictional forces produced by the multiple combinations used in our study design, namely, two bracket materials (metal and ceramic), two archwire materials (stainless steel and coated stainless steel) and three ligation materials (elastomeric, stainless steel and coated stainless steel).

### 1.5. Purpose, Specific Aims and Hypotheses

#### 1.5.1. Purpose

1. To investigate if there is an association between ligature material and frictional force during orthodontic cuspid retraction
2. To compare the differences in resistance to sliding between conventional metallic orthodontic appliances and esthetic orthodontic appliances

#### 1.5.2. Specific Aims:

1. To measure and evaluate if the combination of stainless steel bracket, stainless steel archwire and stainless steel ligature will have a statistically lower mean

static and kinetic frictional resistance compared to ceramic bracket, coated archwire and coated ligature.

2. To measure and evaluate if the combination of stainless steel bracket, coated archwire and coated ligature will have a statistically lower mean static and kinetic frictional resistance compared to all other combinations.

3. To measure and evaluate various combinations of brackets, archwires and ligatures to find the most ideal combination with the least amount of mean static and kinetic frictional resistance.

### 1.5.3. Hypothesis:

**$H_0$:**

There is no association between frictional resistance created by the effect of ligation materials on various combinations of conventional metallic and ceramic bracket/archwire while sliding a bracket along an archwire span.

# Chapter 2: Materials and Methods

## 2.1 Study Description

To achieve a power of 80% with an alpha of 0.05, and an effect size of .25 (Cohen's F), 6 measurements per group were conducted. Two types of brackets, two types of archwires and three types of ligatures were used for this study. We had a total of twelve groups (Figure 3). Each test was run six times. This provided us with a sample size of 72. This incorporates the potential for loss during the study design. The effect size is based off of previous friction studies that showed statistical significance.[1,2]

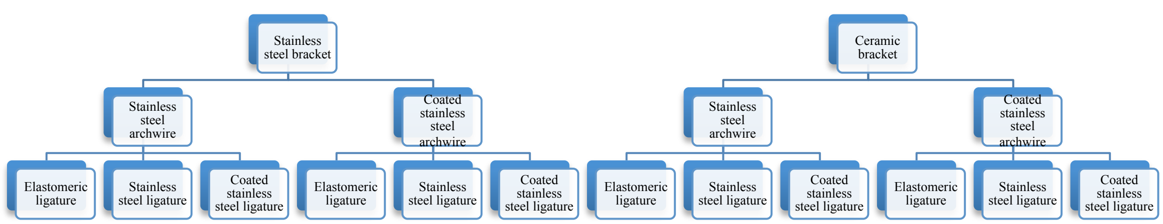


**Figure 3. Flow chart of the groups**

**Brackets:**

The following 0.022” slot standard edgewise, maxillary upper right first premolar brackets with RT prescription were used:

1. Convention stainless steel twin brackets (OmniArch, DENTSPLY GAC)
2. Ceramic twin brackets (Ovation C, DENTSPLY GAC)

RT prescription brackets sold by DENTSPLY GAC have values that are equivalent to the Roth prescription.

**Archwires:**

60mm straight lengths of the following 0.017x0.025” archwires were utilized because they are commonly used for canine retraction with a 0.022” slot:

1. 17x25 Stainless steel archwires (ORTHO TECHNOLOGY)
2. 17x25 Epoxy-coated stainless steel archwires (ORTHO TECHNOLOGY)

Epoxy coating adds .002" thickness to diameter.

**Ligation Materials:**

Three different types of ligatures were used for this study:

1. Elastomeric ligatures (DENTSPLY GAC)
2. 0.010” Stainless steel ligatures (DENTSPLY GAC)
3. 0.010” Teflon-coated stainless steel ligatures (ORTHO TECHNOLOGY)

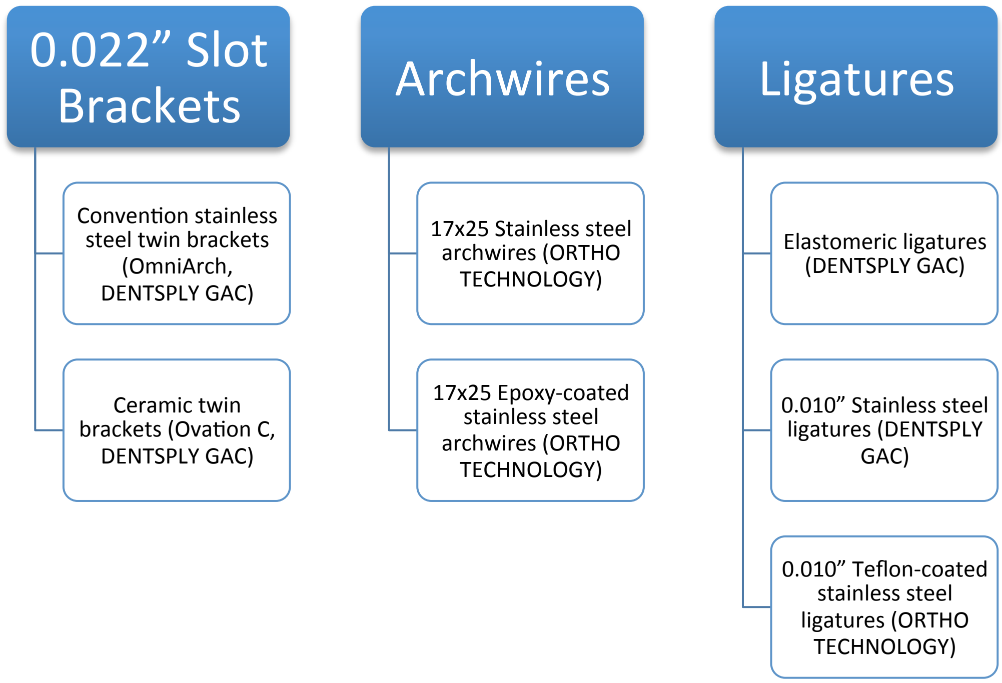


**Figure 4. Materials used**

**Jig:**

A custom made apparatus was fabricated to hold the brackets, archwire and ligatures to test the frictional resistance with the help of a universal strength testing machine, as seen in Figure 5.

**Machine:**

A universal strength testing machine (Instron, Grove City, PA) was used to perform the test. (Figure 6)

### 2.1.1 IRB Approval

IRB approval was not required to conduct this research. There was no protected information, human/animal subjects nor tissues used for this study.

### 2.1.2 Ethical Issues

No potential ethical issues were identified as part of this research study.

### 2.1.3 Grant

This study was awarded a grant by the Health Professions Division at Nova Southeastern University.

### 2.2. Sample Preparation

For each sample, five upper right first premolar brackets with RT prescription in 0.022” slot size were used. The types of brackets utilized in this study were stainless steel and ceramic. Four of the five brackets were aligned using a 0.019x0.025” stainless steel wire and super glued to a rigid Plexiglass clear acrylic sheet using Loctite® Super Glue. A quarter inch thick acrylic sheet was cut into six by nine inch rectangles with a 14mm slit in the bottom center. This was accomplished with the help of Harvey Development Corp, Custom Manufacturing and Millwork, Fort Lauderdale. An inter-bracket distance of 8mm was utilized. 14mm interval at the center was left to allow for the sliding of the test bracket (Figure 5).

This movable test bracket was fitted with a 0.045” thick stainless steel arm on the bonding surface of the bracket with light cure Transbond™ XT composite material. The arm was 10 mm long to represent the distance of the center of resistance of a canine to the bracket slot. A weight of 100gm was suspended from the arm to represent the force acting at the center of resistance of the canine. A set-up such as this allows us to achieve a scenario that will be as close as possible to a clinical situation. The archwire was ligated to the brackets using 0.010” stainless steel, 0.010” coated stainless steel or elastomeric ligatures. The stainless steel ligatures were tightened until taut and then loosened by one turn.

**2.3. Experiment**

The Plexiglass jig was mounted on the Universal Testing Machine (Instron, Grove City, PA) and each group was tested by sliding the movable bracket along the archwire. This movable bracket was connected to the moveable crosshead of the testing machine with the help of a 0.010” stainless steel ligature. The bracket was pulled at a velocity of 2.5mm/min for a total test distance of 5mm, following the method of Khamatkar et al (Figure 6).[2]

For each test, the acrylic jig was removed from the machine and the bracket, archwires and ligatures were replaced. All groups were tested using the same protocol as above. Mean kinetic friction was measured for 120 seconds at ten second intervals, beginning at the 30-second time point. Maximum static and mean kinetic friction measurements were repeated six times and the mean was calculated for each bracket, archwire and ligature combination. A single operator performed all adjustments, ligations and measurements to ensure consistency.

### 2.4. Statistical Analysis

A three-way ANOVA was run on a sample size of 72 to examine the effect of bracket material, archwire material and ligature material on maximum static and mean kinetic friction. Any differences found within and/or between the groups were further analyzed using the Tukey's Pairwise Comparison test.

**Figure 5. Acrylic sheet with mounted brackets and archwire**

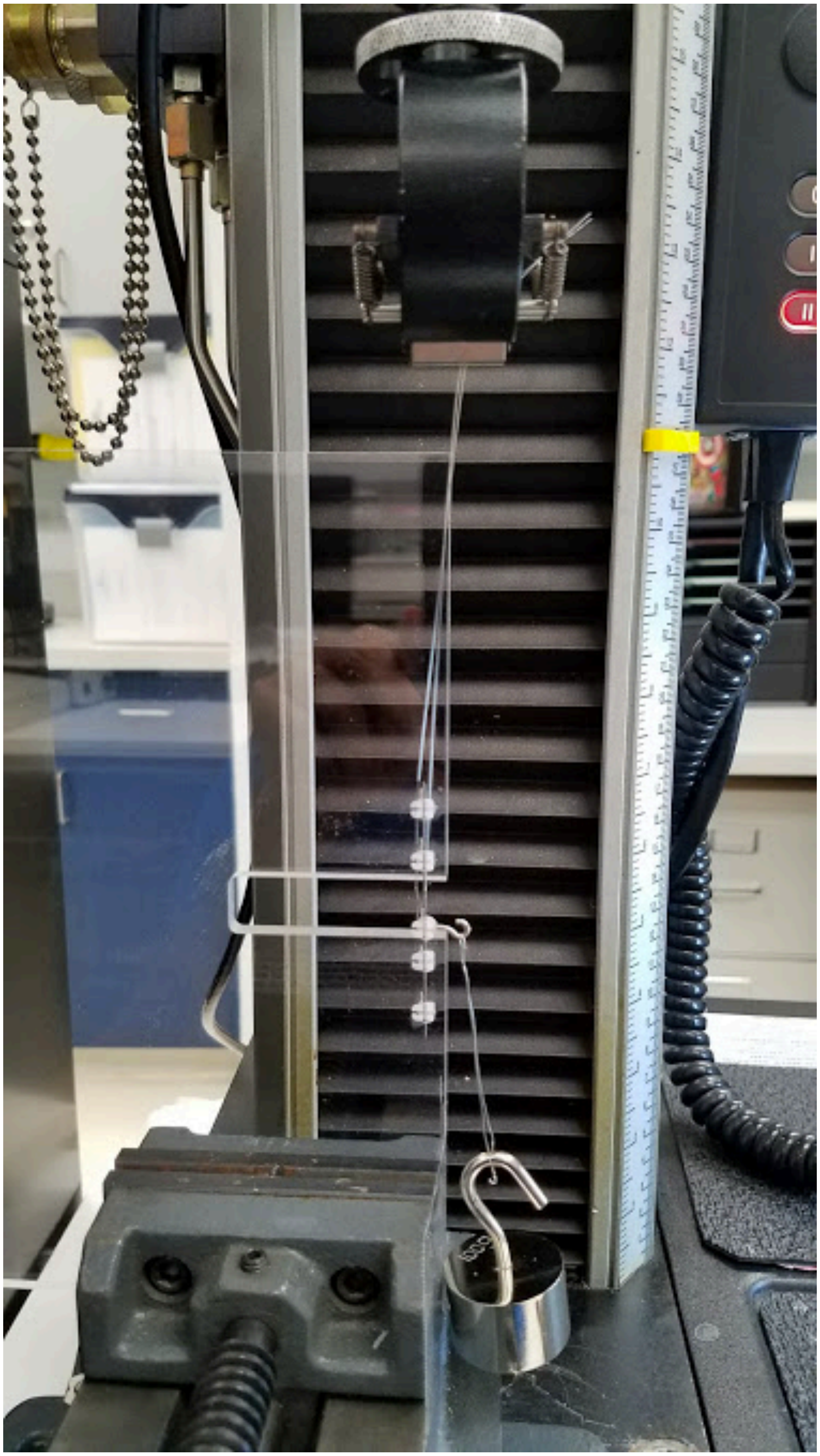

**Figure 6. Acrylic jig mounted on the Instron machine**

# Chapter 3: Results

The data collected from this study consisted of two dependent variables associated with each sample: maximum static friction and mean kinetic friction. Both of these variables were measured in Newtons (N). With the help of the Instron machine, the total force required to move the bracket a distance of five millimeters was measured. Since, in our experiment, we used a weight of 100gm to depict the force acting at the center of resistance of the canine, this value was deducted from the total force required to give us the value of maximum static and mean kinetic frictional forces. 1N = 101.97gm.

### 3.1 Descriptive Statistics for Maximum Static and Mean Kinetic Friction

The descriptive statistics for maximum static and mean kinetic friction are listed in Tables 1 and 2 respectively. The interaction of ceramic bracket, coated archwire and coated ligature produced the lowest maximum static friction, whereas the combination of stainless steel bracket, coated archwire and elastomeric ligature showed the highest maximum static frictional values. Among the stainless steel bracket group, the lowest maximum static frictional forces were seen with stainless steel wire and coated ligature. A similar trend was seen for the values of mean kinetic friction, except in the stainless steel bracket group. Here, the combination of stainless steel brackets, stainless steel archwires and stainless steel ligatures produced the least amount of mean kinetic friction. These relationships between brackets, archwires and ligatures can also be seen in barplot graphs in Figures 7 and 8.

**Table 1. Descriptive Statistics for Maximum Static Friction**

| Bracket | Wire | Ligature | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|---|---|
| Ceramic bracket | Coated wire | Coated ligature | 6 | 0.45 | 0.05 | 0.40 | 0.50 |
| Ceramic bracket | Coated wire | Elastomeric ligature | 6 | 1.85 | 0.10 | 1.70 | 2.00 |
| Ceramic bracket | Coated wire | SS ligature | 6 | 1.58 | 0.35 | 1.20 | 2.20 |
| Ceramic bracket | SS wire | Coated ligature | 6 | 1.30 | 0.14 | 1.10 | 1.50 |
| Ceramic bracket | SS wire | Elastomeric ligature | 6 | 2.10 | 0.25 | 1.90 | 2.50 |
| Ceramic bracket | SS wire | SS ligature | 6 | 1.42 | 0.04 | 1.40 | 1.50 |
| SS bracket | Coated wire | Coated ligature | 6 | 2.40 | 0.80 | 1.40 | 3.30 |
| SS bracket | Coated wire | Elastomeric ligature | 6 | 4.53 | 1.56 | 3.20 | 7.60 |
| SS bracket | Coated wire | SS ligature | 6 | 3.22 | 1.33 | 2.20 | 5.60 |
| SS bracket | SS wire | Coated ligature | 6 | 1.35 | 0.18 | 1.00 | 1.50 |
| SS bracket | SS wire | Elastomeric ligature | 6 | 2.03 | 0.10 | 1.90 | 2.20 |
| SS bracket | SS wire | SS ligature | 6 | 1.47 | 0.26 | 1.10 | 1.80 |

*SS- stainless steel. Unit of force=Newton

**Table 2. Descriptive Statistics for Mean Kinetic Friction**

| Bracket | Wire | Ligature | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|---|---|
| Ceramic bracket | Coated wire | Coated ligature | 6 | 0.27 | 0.05 | 0.20 | 0.30 |
| Ceramic bracket | Coated wire | Elastomeric ligature | 6 | 1.62 | 0.12 | 1.50 | 1.80 |
| Ceramic bracket | Coated wire | SS ligature | 6 | 1.15 | 0.24 | 0.90 | 1.50 |
| Ceramic bracket | SS wire | Coated ligature | 6 | 1.13 | 0.10 | 1.00 | 1.30 |
| Ceramic bracket | SS wire | Elastomeric ligature | 6 | 1.87 | 0.27 | 1.60 | 2.20 |
| Ceramic bracket | SS wire | SS ligature | 6 | 1.23 | 0.05 | 1.20 | 1.30 |
| SS bracket | Coated wire | Coated ligature | 6 | 1.77 | 0.31 | 1.20 | 2.10 |
| SS bracket | Coated wire | Elastomeric ligature | 6 | 3.88 | 1.49 | 2.70 | 6.60 |
| SS bracket | Coated wire | SS ligature | 6 | 2.50 | 0.61 | 1.90 | 3.40 |
| SS bracket | SS wire | Coated ligature | 6 | 1.23 | 0.15 | 1.00 | 1.40 |
| SS bracket | SS wire | Elastomeric ligature | 6 | 2.03 | 0.29 | 1.80 | 2.40 |
| SS bracket | SS wire | SS ligature | 6 | 1.18 | 0.24 | 1.00 | 1.60 |

*SS- stainless steel. Unit of force=Newton

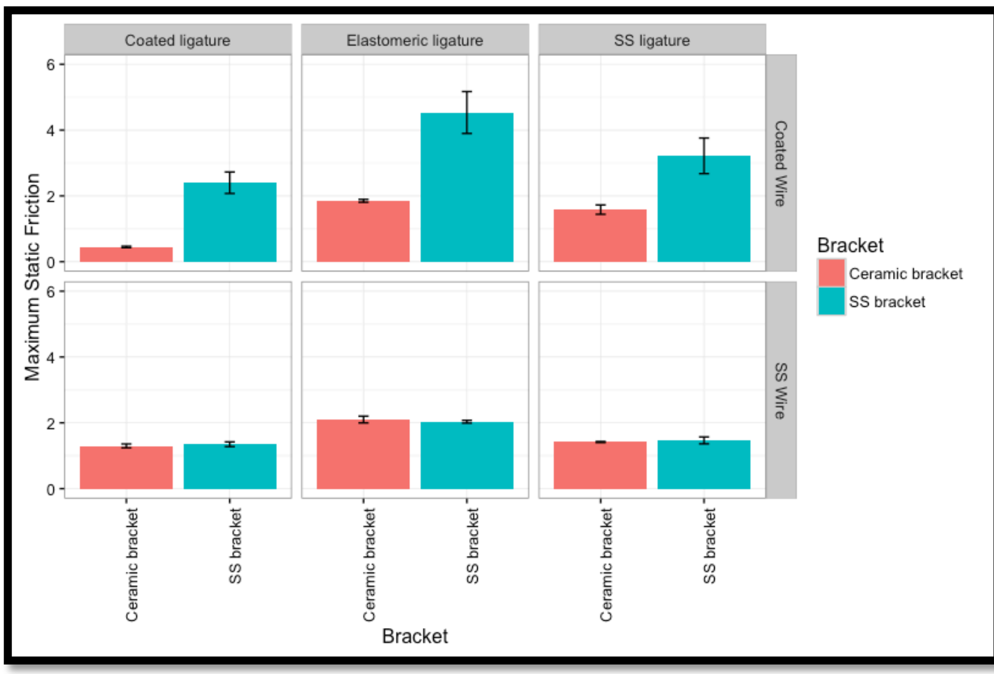


**Figure 7. Barplots with 95% Confidence Intervals for Maximum Static Friction**

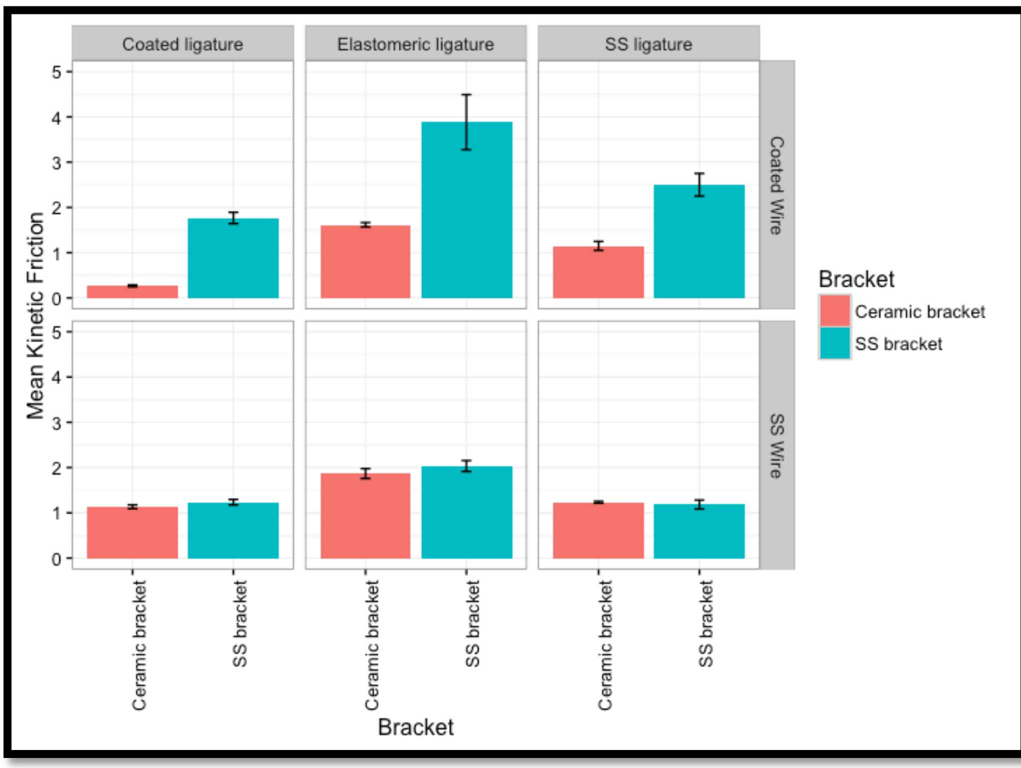


**Figure 8. Barplots with 95% Confidence Intervals for Mean Kinetic Friction**

### 3.2 Statistical Analysis of Data

A three-way analysis-of-variance (ANOVA) was run on a sample size of 72 to examine the effect of bracket material (stainless steel vs. ceramic), archwire material (stainless steel vs. coated stainless steel) and ligature material (elastomeric vs. stainless steel vs. coated stainless steel). A statistically significant difference on the dependent variable was considered to be one that would have occurred by chance in less than five of every one hundred observations ($p \leq 0.05$).

The results of ANOVA for maximum static and mean kinetic friction are listed in Tables 3 and 4 respectively. For the dependent variable, maximum static friction, the bracket material, archwire material and the ligature material each show a significant difference. The bracket material was associated with 20% of the variability in the maximum static friction, whereas the archwire accounts for 10% and the ligature is responsible for 19%.

A significant difference in maximum static friction was noted in the interaction between bracket and archwire material, and archwire and ligature material. But the combination of bracket and ligature material did not produce a significant difference in the maximum static friction values, which accounted for only 1% variability. The bracket and archwire material was responsible for 20% variability and the archwire and ligature material showed a variability of 4% in maximum static friction.

The interaction between bracket, archwire and ligature material accounted for only 1% of the variability in maximum static friction, which was not statistically significant. These relationships can also be visualized using the pie charts seen in Figures 9 and 10.

**Table 3. Three-way ANOVA for Maximum Static Friction and Mean Kinetic Friction**

**Maximum Static Friction**

| | Df | Sum Sq | Mean Sq | F value | Pr(>F) | |
|---|---|---|---|---|---|---|
| Bracket | 1 | 19.845 | 19.845 | 46.133 | 0.000 | *** |
| Wire | 1 | 9.534 | 9.534 | 22.163 | 0.000 | *** |
| Ligature | 2 | 18.981 | 9.490 | 22.062 | 0.000 | *** |
| Bracket:Wire | 1 | 19.427 | 19.427 | 45.162 | 0.000 | *** |
| Bracket:Ligature | 2 | 0.676 | 0.338 | 0.786 | 0.461 | |
| Wire:Ligature | 2 | 3.630 | 1.815 | 4.220 | 0.019 | * |
| Bracket:Wire:Ligature | 2 | 1.092 | 0.546 | 1.269 | 0.289 | |
| Residuals | 60 | 25.810 | 0.430 | | | |

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

**Mean Kinetic Friction**

| | Df | Sum Sq | Mean Sq | F value | Pr(>F) | |
|---|---|---|---|---|---|---|
| Bracket | 1 | 14.222 | 14.222 | 56.612 | 0.000 | *** |
| Wire | 1 | 3.125 | 3.125 | 12.439 | 0.001 | *** |
| Ligature | 2 | 19.444 | 9.722 | 38.700 | 0.000 | *** |
| Bracket:Wire | 1 | 12.005 | 12.005 | 47.786 | 0.000 | *** |
| Bracket:Ligature | 2 | 1.034 | 0.517 | 2.059 | 0.137 | |
| Wire:Ligature | 2 | 3.163 | 1.582 | 6.296 | 0.003 | ** |
| Bracket:Wire:Ligature | 2 | 0.490 | 0.245 | 0.975 | 0.383 | |
| Residuals | 60 | 15.073 | 0.251 | | | |

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '

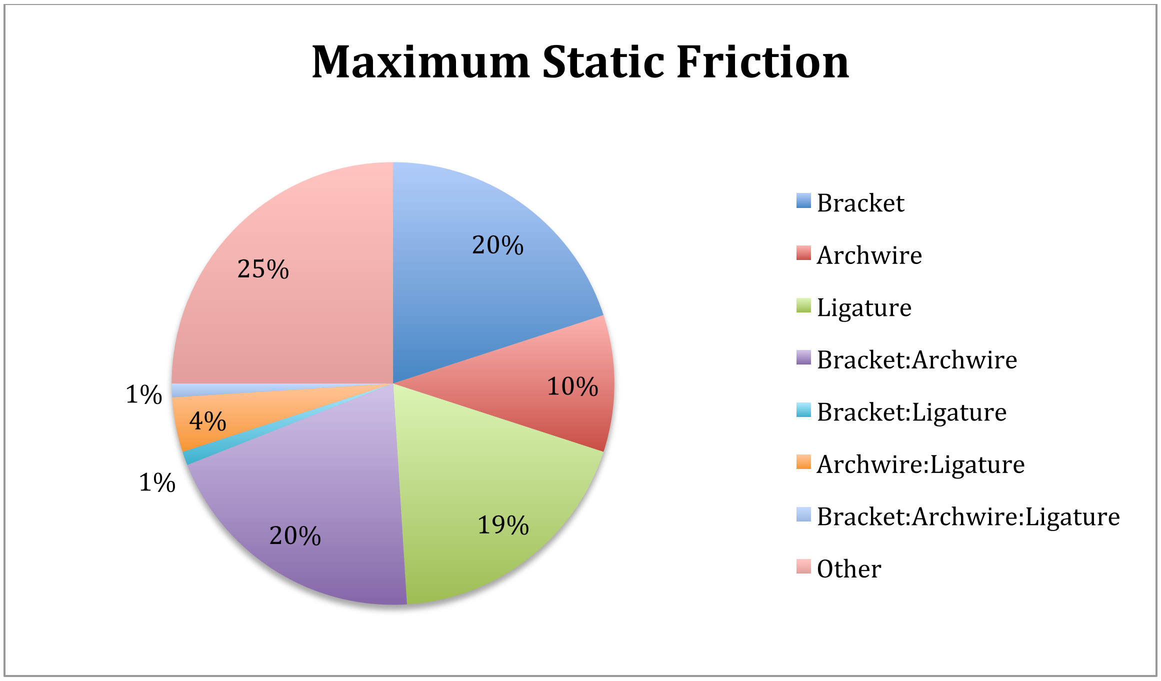


**Figure 9. Pie chart of three-way ANOVA for Maximum Static Friction**

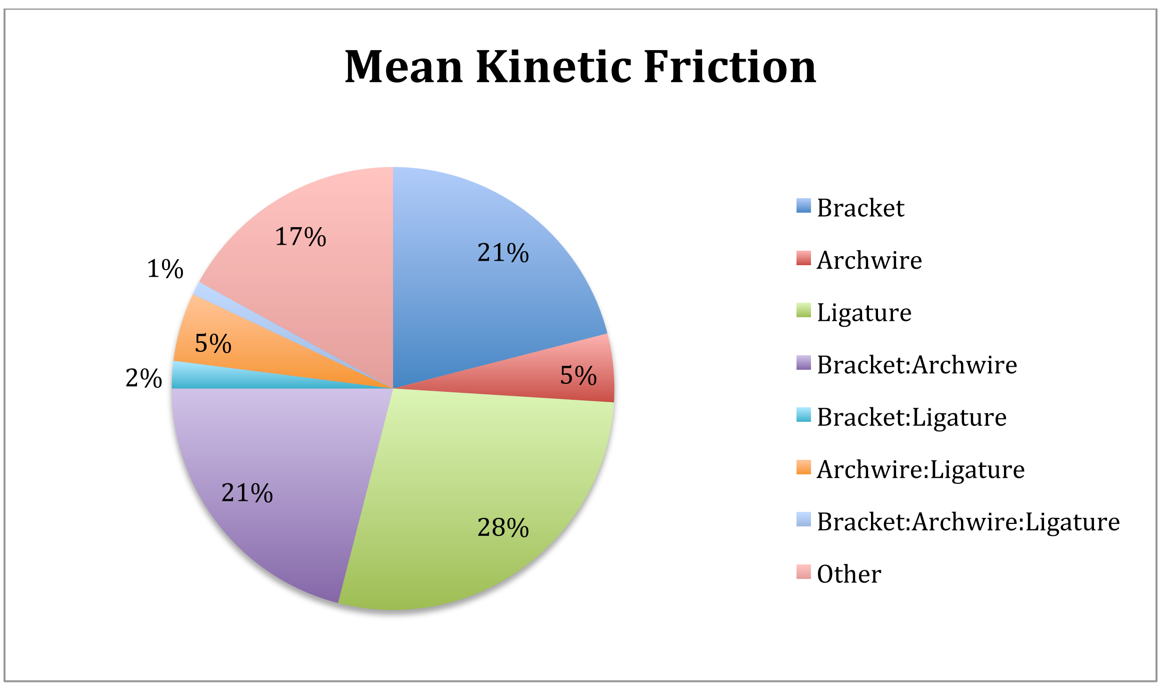


**Figure 10. Pie chart of three-way ANOVA for Mean Kinetic Friction**

The results of the three-way ANOVA for mean kinetic friction were similar to that of the maximum kinetic friction (Table 4). Bracket, archwire and ligature material individually showed significant differences by accounting for 21%, 5% and 28% variability in mean kinetic friction respectively. No significant difference was observed in the combination of bracket and ligature material. The interaction of all three materials also did not produce a statistically significant difference, comparable to the relationship seen with the values of maximum static friction.

When statistically significant differences were noted between either dependent or independent variables, Tukey's Pairwise Comparisons test was carried out. The results of the maximum static and mean kinetic friction were similar (Tables 5 and 6). The stainless steel brackets produced more frictional resistance than their ceramic counterparts. The friction produced by coated archwires was less than that of stainless steel archwires. The pairwise comparisons also showed that the elastomeric ligatures accounted for more frictional resistance followed by stainless steel ligatures. The coated stainless steel ligatures were associated with the lowest frictional values.

## Table 4. Tukey's Pairwise Comparisons for Maximum Static Friction

| Parameter | Comparison | Diff. | LC | UL | Sig |
|---|---|---|---|---|---|
| Bracket | SS Bracket-Ceramic bracket | 1.05 | 0.74 | 1.36 | 0.000 |
| Wire | SS Wire-Coated Wire | -0.73 | -1.04 | -0.42 | 0.000 |
| Ligature | Elastomeric Ligature-Coated ligature | 1.25 | 0.80 | 1.71 | 0.000 |
| Ligature | SS Ligature-Coated ligature | 0.55 | 0.09 | 1.00 | 0.015 |
| Ligature | SS Ligature-Elastomeric ligature | -0.71 | -1.16 | -0.25 | 0.001 |
| Bracket:Wire | SS bracket: Coated Wire-Ceramic bracket: Coated Wire | 2.09 | 1.51 | 2.67 | 0.000 |
| Bracket:Wire | Ceramic bracket:SS Wire-Ceramic bracket: Coated Wire | 0.31 | -0.27 | 0.89 | 0.490 |
| Bracket:Wire | SS bracket:SS Wire-Ceramic bracket: Coated Wire | 0.32 | -0.26 | 0.90 | 0.459 |
| Bracket:Wire | Ceramic bracket:SS Wire-SS bracket: Coated Wire | -1.78 | -2.36 | -1.20 | 0.000 |
| Bracket:Wire | SS bracket:SS Wire-SS bracket: Coated Wire | -1.77 | -2.34 | -1.19 | 0.000 |
| Bracket:Wire | SS bracket:SS Wire-Ceramic bracket:SS Wire | 0.01 | -0.57 | 0.59 | 1.000 |
| Bracket: Ligature | SS bracket: Coated Ligature-Ceramic bracket: Coated ligature | 1.00 | 0.21 | 1.79 | 0.005 |
| Bracket: Ligature | Ceramic bracket: Elastomeric Ligature-Ceramic bracket: Coated ligature | 1.10 | 0.31 | 1.89 | 0.002 |
| Bracket: Ligature | SS bracket: Elastomeric Ligature-Ceramic bracket: Coated ligature | 2.41 | 1.62 | 3.20 | 0.000 |
| Bracket: Ligature | Ceramic bracket:SS Ligature-Ceramic bracket: Coated ligature | 0.63 | -0.16 | 1.41 | 0.197 |
| Bracket: Ligature | SS bracket:SS Ligature-Ceramic bracket: Coated ligature | 1.47 | 0.68 | 2.25 | 0.000 |
| Bracket: Ligature | Ceramic bracket: Elastomeric ligature-SS bracket: Coated ligature | 0.10 | -0.69 | 0.89 | 0.999 |
| Bracket: Ligature | SS bracket: Elastomeric ligature-SS bracket: Coated ligature | 1.41 | 0.62 | 2.20 | 0.000 |
| Bracket: Ligature | Ceramic bracket:SS ligature-SS bracket: Coated ligature | -0.38 | -1.16 | 0.41 | 0.727 |
| Bracket: Ligature | SS bracket:SS ligature-SS bracket: Coated ligature | 0.47 | -0.32 | 1.25 | 0.510 |
| Bracket: Ligature | SS bracket: Elastomeric Ligature-Ceramic bracket: Elastomeric ligature | 1.31 | 0.52 | 2.10 | 0.000 |
| Bracket: Ligature | Ceramic bracket:SS Ligature-Ceramic bracket: Elastomeric ligature | -0.48 | -1.26 | 0.31 | 0.490 |
| Bracket: Ligature | SS bracket:SS Ligature-Ceramic bracket: Elastomeric ligature | 0.37 | -0.42 | 1.15 | 0.745 |
| Bracket: Ligature | Ceramic bracket:SS ligature-SS bracket: Elastomeric ligature | -1.78 | -2.57 | -1.00 | 0.000 |
| Bracket: Ligature | SS bracket:SS ligature-SS bracket: Elastomeric ligature | -0.94 | -1.73 | -0.15 | 0.010 |
| Bracket: Ligature | SS bracket:SS Ligature-Ceramic bracket:SS ligature | 0.84 | 0.05 | 1.63 | 0.030 |
| Wire: Ligature | SS Wire: Coated Ligature-Coated Wire: Coated ligature | -0.10 | -0.89 | 0.69 | 0.999 |
| Wire: Ligature | Coated Wire: Elastomeric Ligature-Coated Wire: Coated ligature | 1.77 | 0.98 | 2.55 | 0.000 |
| Wire: Ligature | SS Wire: Elastomeric Ligature-Coated Wire: Coated ligature | 0.64 | -0.15 | 1.43 | 0.174 |
| Wire: Ligature | Coated Wire:SS Ligature-Coated Wire: Coated ligature | 0.98 | 0.19 | 1.76 | 0.007 |
| Wire: Ligature | SS Wire:SS Ligature-Coated Wire: Coated ligature | 0.02 | -0.77 | 0.80 | 1.000 |
| Wire: Ligature | Coated Wire: Elastomeric ligature-SS Wire: Coated ligature | 1.87 | 1.08 | 2.65 | 0.000 |
| Wire: Ligature | SS Wire: Elastomeric ligature-SS Wire: Coated ligature | 0.74 | -0.05 | 1.53 | 0.077 |
| Wire: Ligature | Coated Wire:SS ligature-SS Wire: Coated ligature | 1.08 | 0.29 | 1.86 | 0.002 |
| Wire: Ligature | SS Wire:SS ligature-SS Wire: Coated ligature | 0.12 | -0.67 | 0.90 | 0.998 |
| Wire: Ligature | SS Wire: Elastomeric Ligature-Coated Wire: Elastomeric ligature | -1.13 | -1.91 | -0.34 | 0.001 |
| Wire: Ligature | Coated Wire:SS Ligature-Coated Wire: Elastomeric ligature | -0.79 | -1.58 | 0.00 | 0.048 |
| Wire: Ligature | SS Wire:SS Ligature-Coated Wire: Elastomeric ligature | -1.75 | -2.54 | -0.96 | 0.000 |
| Wire: Ligature | Coated Wire:SS ligature-SS Wire: Elastomeric ligature | 0.33 | -0.45 | 1.12 | 0.813 |
| Wire: Ligature | SS Wire:SS ligature-SS Wire: Elastomeric ligature | -0.62 | -1.41 | 0.16 | 0.197 |
| Wire: Ligature | SS Wire:SS Ligature-Coated Wire:SS ligature | -0.96 | -1.75 | -0.17 | 0.009 |

## Table 5. Tukey's Pairwise Comparisons for Mean Kinetic Friction

| Parameter | Comparison | Diff. | LC | UL | Sig |
|---|---|---|---|---|---|
| Bracket | SS Bracket-Ceramic bracket | 0.89 | 0.65 | 1.13 | 0.000 |
| Wire | SS Wire-Coated Wire | -0.42 | -0.65 | -0.18 | 0.001 |
| Ligature | Elastomeric Ligature-Coated ligature | 1.25 | 0.90 | 1.60 | 0.000 |
| Ligature | SS Ligature-Coated ligature | 0.42 | 0.07 | 0.76 | 0.015 |
| Ligature | SS Ligature-Elastomeric ligature | -0.83 | -1.18 | -0.49 | 0.000 |
| Bracket:Wire | SS bracket: Coated Wire-Ceramic bracket: Coated Wire | 1.71 | 1.26 | 2.15 | 0.000 |
| Bracket:Wire | Ceramic bracket:SS Wire-Ceramic bracket: Coated Wire | 0.40 | -0.04 | 0.84 | 0.089 |
| Bracket:Wire | SS bracket:SS Wire-Ceramic bracket: Coated Wire | 0.47 | 0.03 | 0.91 | 0.032 |
| Bracket:Wire | Ceramic bracket:SS Wire-SS bracket: Coated Wire | -1.31 | -1.75 | -0.86 | 0.000 |
| Bracket:Wire | SS bracket:SS Wire-SS bracket: Coated Wire | -1.23 | -1.67 | -0.79 | 0.000 |
| Bracket:Wire | SS bracket:SS Wire-Ceramic bracket:SS Wire | 0.07 | -0.37 | 0.51 | 0.973 |
| Bracket: Ligature | SS bracket: Coated Ligature-Ceramic bracket: Coated ligature | 0.80 | 0.20 | 1.40 | 0.003 |
| Bracket: Ligature | Ceramic bracket: Elastomeric Ligature-Ceramic bracket: Coated ligature | 1.04 | 0.44 | 1.64 | 0.000 |
| Bracket: Ligature | SS bracket: Elastomeric Ligature-Ceramic bracket: Coated ligature | 2.26 | 1.66 | 2.86 | 0.000 |
| Bracket: Ligature | Ceramic bracket:SS Ligature-Ceramic bracket: Coated ligature | 0.49 | -0.11 | 1.09 | 0.172 |
| Bracket: Ligature | SS bracket:SS Ligature-Ceramic bracket: Coated ligature | 1.14 | 0.54 | 1.74 | 0.000 |
| Bracket: Ligature | Ceramic bracket: Elastomeric ligature-SS bracket: Coated ligature | 0.24 | -0.36 | 0.84 | 0.844 |
| Bracket: Ligature | SS bracket: Elastomeric ligature-SS bracket: Coated ligature | 1.46 | 0.86 | 2.06 | 0.000 |
| Bracket: Ligature | Ceramic bracket:SS ligature-SS bracket: Coated ligature | -0.31 | -0.91 | 0.29 | 0.661 |
| Bracket: Ligature | SS bracket:SS ligature-SS bracket: Coated ligature | 0.34 | -0.26 | 0.94 | 0.557 |
| Bracket: Ligature | SS bracket: Elastomeric Ligature-Ceramic bracket: Elastomeric ligature | 1.22 | 0.61 | 1.82 | 0.000 |
| Bracket: Ligature | Ceramic bracket:SS Ligature-Ceramic bracket: Elastomeric ligature | -0.55 | -1.15 | 0.05 | 0.093 |
| Bracket: Ligature | SS bracket:SS Ligature-Ceramic bracket: Elastomeric ligature | 0.10 | -0.50 | 0.70 | 0.996 |
| Bracket: Ligature | Ceramic bracket:SS ligature-SS bracket: Elastomeric ligature | -1.77 | -2.37 | -1.16 | 0.000 |
| Bracket: Ligature | SS bracket:SS ligature-SS bracket: Elastomeric ligature | -1.12 | -1.72 | -0.51 | 0.000 |
| Bracket: Ligature | SS bracket:SS Ligature-Ceramic bracket:SS ligature | 0.65 | 0.05 | 1.25 | 0.027 |
| Wire: Ligature | SS Wire: Coated Ligature-Coated Wire: Coated ligature | 0.17 | -0.44 | 0.77 | 0.964 |
| Wire: Ligature | Coated Wire: Elastomeric Ligature-Coated Wire: Coated ligature | 1.73 | 1.13 | 2.34 | 0.000 |
| Wire: Ligature | SS Wire: Elastomeric Ligature-Coated Wire: Coated ligature | 0.93 | 0.33 | 1.54 | 0.000 |
| Wire: Ligature | Coated Wire:SS Ligature-Coated Wire: Coated ligature | 0.81 | 0.21 | 1.41 | 0.003 |
| Wire: Ligature | SS Wire:SS Ligature-Coated Wire: Coated ligature | 0.19 | -0.41 | 0.79 | 0.935 |
| Wire: Ligature | Coated Wire: Elastomeric ligature-SS Wire: Coated ligature | 1.57 | 0.96 | 2.17 | 0.000 |
| Wire: Ligature | SS Wire: Elastomeric ligature-SS Wire: Coated ligature | 0.77 | 0.16 | 1.37 | 0.005 |
| Wire: Ligature | Coated Wire:SS ligature-SS Wire: Coated ligature | 0.64 | 0.04 | 1.24 | 0.030 |
| Wire: Ligature | SS Wire:SS ligature-SS Wire: Coated ligature | 0.02 | -0.58 | 0.63 | 1.000 |
| Wire: Ligature | SS Wire: Elastomeric Ligature-Coated Wire: Elastomeric ligature | -0.80 | -1.40 | -0.20 | 0.003 |
| Wire: Ligature | Coated Wire:SS Ligature-Coated Wire: Elastomeric ligature | -0.93 | -1.53 | -0.32 | 0.000 |
| Wire: Ligature | SS Wire:SS Ligature-Coated Wire: Elastomeric ligature | -1.54 | -2.14 | -0.94 | 0.000 |
| Wire: Ligature | Coated Wire:SS ligature-SS Wire: Elastomeric ligature | -0.13 | -0.73 | 0.48 | 0.990 |
| Wire: Ligature | SS Wire:SS ligature-SS Wire: Elastomeric ligature | -0.74 | -1.34 | -0.14 | 0.008 |
| Wire: Ligature | SS Wire:SS Ligature-Coated Wire:SS ligature | -0.62 | -1.22 | -0.01 | 0.042 |

# Chapter 4: Discussion

The purpose of this study was to evaluate the association between ligation material and frictional force during orthodontic cuspid retraction and to compare the differences in resistance to sliding between conventional metallic orthodontic appliances and esthetic orthodontic appliances. Each test specimen consisted of an orthodontic bracket (stainless steel or ceramic), a segment of an archwire (stainless steel or epoxy-coated stainless steel) and a ligature (elastomeric, stainless steel or Teflon-coated stainless steel).

Within each subsample, maximum static and mean kinetic frictional forces were evaluated individually and with respect to each other. With the classic block-on-plane model, frictional forces generally decrease after initiation of movement and then remain relatively constant during motion, a relationship that was also observed during this study. The combined average of all tests provided mean maximum static frictional forces that were slightly greater than the mean kinetic frictional forces. This trend, seen in the values of static and kinetic frictional forces, was similar between all groups and hence for the sake of simplicity in discussion, they will be referred to collectively as frictional forces, unless otherwise stated.

The Tukey's Pairwise Comparisons indicated significant differences between frictional forces produced by brackets, archwires and ligatures. The stainless steel bracket was associated with significantly higher frictional forces than ceramic brackets. This difference was more apparent with the use of epoxy-coated stainless steel archwires. When uncoated stainless steel archwires were used, no significant difference in frictional forces was noted between the two types of brackets. Numerous studies in the past have shown that stainless steel brackets produce less frictional resistance than ceramic brackets.[19,23-25] Kusy et al, Ireland et al and Omana et al have reported that ceramic brackets show similar or even lower frictional resistance than stainless steel brackets, a finding similar to this study.[7,26,27] Ireland et al stated that clinically there might be little to choose between stainless steel and ceramic brackets in the buccal segments, with choice of archwire being more important.[26] Omana et al suggested that their findings of reduced friction with ceramic brackets might be due to the injection-molding manufacturing process that produces very smooth surfaces.[27]

The Ovation-C ceramic bracket used in this study is made from mono-crystalline Aluminum Oxide. Gill et al evaluated frictional forces between stainless steel, mono-crystalline and poly-crystalline brackets and found that poly-crystalline brackets produced the highest frictional forces, whereas the values for stainless steel and mono-crystalline brackets were not statistically significant. They also examined the surfaces of the brackets under a microscope. The poly-crystalline brackets had a coarser surface texture and more prominent surface irregularities than mono-crystalline or stainless steel brackets.[4]

Uncoated stainless steel archwires were found to generate significantly less frictional forces than the epoxy-coated stainless steel archwires, according to the Tukey's Pairwise Comparison test. These values might be skewed due to the higher frictional forces produced with the combination of stainless steel brackets and coated archwires. One of the factors that might have played a role in higher values of friction being produced between stainless steel brackets and coated archwires could be fragmentation of the coating on the archwire. Elayyan et al conducted a study to investigate the mechanical properties of coated archwires. They reported that the esthetic coating is not durable and there is fragmentation of the coating. This causes excessive friction between the archwire and the bracket and is most likely due to damage to the coating ‘ jamming ’ the wire in place.[48]

The increased fragmentation and frictional forces were seen in this study when the coated archwires were used in combination with stainless steel brackets. A similar relationship was not seen when these archwires were used with ceramic brackets. A possible explanation for that could be the difference in shape of the bracket slot-edge of the two brackets. The Ovation-C ceramic brackets have triple-chamfered slot walls, which provide a very rounded and smooth bracket slot-edge. This could possibly decrease the opportunity for binding and notching of the archwire. The OmniArch stainless steel brackets do not have this feature. The slot walls of this bracket are single-chamfered and the bracket slot-edges are not as rounded. The difference in bracket slot-edges of both brackets can be seen in Figure. 11 below.

**Figure 11. Bracket slot-edges of the OmniArch and Ovation-C brackets**

The method of ligation plays a crucial role in the generation of frictional forces at the bracket-archwire interface. The comparison of different ligature materials used in this study agrees with the results of previous studies.[1,32-35] The elastomeric ligatures produced the highest amount of frictional forces followed by stainless steel ligatures. The lowest amount of frictional forces was seen with the Teflon-coated stainless steel ligatures. This was true for all the groups analyzed.

The results of this study are similar to those reported by Edwards et al, who evaluated the difference in frictional forces produced by different ligatures in conjunction with stainless steel brackets and archwires. They also found that that Teflon-coated ligatures produced the least amount of frictional resistance, followed by uncoated stainless steel and elastomeric ligatures.[35] Similarly, De Franco et al found that Teflon-coated ligatures had lower frictional force values regardless of the bracket and archwire type. They suggested that the lower frictional forces produced were due to the lower coefficient of friction of Teflon.[1]

When comparing between the 12 groups, the group with ceramic bracket, coated stainless steel archwire and coated ligature produced the least amount of frictional resistance. The highest frictional forces were produced by the combination of stainless steel bracket, coated archwire and elastomeric ligature. When the groups containing stainless steel brackets and coated archwires were removed from the analysis due to increased fragmentation of the coating within this group, no statistically significant differences were found in the frictional forces produced by the remaining nine groups.

These results indicate that ceramic brackets have come a long way since their inception and are comparable to stainless steel brackets in the amount of frictional forces produced. On the other hand, coated archwires are still not as efficient as their uncoated counterparts. This can be attributed to the lack of durability of the surface coating of archwires. This failure creates some question as to the viability of coated archwires at this time, especially when tipping is likely during cuspid retraction.

### 4.1 Limitations and Future Studies

This was a comparative study. *In vitro* friction studies are not capable of simulating clinical conditions with all the attended variables. As with any bench-top study, we cannot accurately simulate *in vivo* orthodontic friction because of variables such as masticatory forces and oral functions, various types of malocclusion, width and compressibility of the periodontal ligament, rotation of teeth, torque at the archwire-bracket interface, presence of moisture and temperature of the oral cavity. One of the biggest limitations of an *in vitro* friction study is to replicate the extremely slow velocity and irregular nature of tooth movement. This slow movement of teeth may produce dynamics that do not correspond to the classical understanding of friction.[10] *In vitro* studies test the samples at constant speeds at magnitudes much greater than that found in the oral cavity.

The materials tested in this study were very limited. Only one type of coated archwire was used of a particular size. Not only are coatings of different materials available, each type of coating produced by various manufactures is not similar to one another. All these materials might have a different coefficient of friction and hence produce frictional forces that might vary. Also, there are numerous other brackets available in the markets that are made of different materials utilizing diverse manufacturing processes. Active and passive self-ligating brackets are also available that were not tested in this study.

Recommendations for future studies would be to test the amount of frictional forces generated by archwires of different coating materials along with ceramic brackets manufactured by multiple companies. Fabrication of a device to replicate the oral environment along with an artificial periodontal ligament-like substance would be beneficial to close the gap between *in vitro* and *in vivo* friction studies.

# Chapter 5: Conclusions

The results of this study show that the method of ligation does play an important role in generating frictional forces at the bracket-archwire interface. The ligature material accounted for 19% of the variability in maximum static friction and 28% of variability in mean kinetic friction. Elastomeric ligatures produced the highest amounts of frictional forces followed by stainless steel ligatures and Teflon-coated stainless steel ligatures.

The least amount of frictional resistance observed was between the interaction of ceramic bracket, epoxy-coated stainless steel archwire and Teflon-coated stainless steel ligature. The metallic appliance composed of stainless steel bracket, archwire and ligatures produced higher frictional forces than their esthetic counterpart, but the difference was not statistically significant.

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# Appendix- Raw Data

| | | | | **Maximum static** | Kinetic 1 | Kinetic 2 | Kinetic 3 | Kinetic 4 | Kinetic 5 | Kinetic 6 | Kinetic 7 | Kinetic 8 | **Mean Kinetic** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SS bracket | SS Wire | Elastomeric ligature | 1 | **2** | 2.4 | 2.3 | 2.4 | 2.4 | 2.3 | 2.4 | 2.4 | 2.2 | **2.4** |
| | | | 2 | **2.2** | 2.1 | 2.3 | 2 | 2.1 | 2 | 1.9 | 2 | 1.8 | **2** |
| | | | 3 | **2.1** | 1.9 | 2.1 | 2.2 | 2.3 | 2.2 | 2.1 | 2.2 | 2.3 | **2.4** |
| | | | 4 | **1.9** | 1.9 | 1.8 | 1.9 | 0.8 | 1.6 | 1.6 | 1.7 | 1.8 | **1.8** |
| | | | 5 | **2** | 1.7 | 1.9 | 2.1 | 0.7 | 1.7 | 1.7 | 1.8 | 2.9 | **1.8** |
| | | | 6 | **2** | 1.4 | 1.9 | 2.2 | 2 | 1.7 | 1.7 | 1.6 | 1.5 | **1.8** |
| | | | | | | | | | | | | | |
| SS bracket | SS wire | SS ligature | 1 | **1.1** | 0.9 | 1 | 1.1 | 1 | 1.2 | 1.1 | 0.9 | 0.6 | **1** |
| | | | 2 | **1.4** | 1.1 | 0.8 | 1.2 | 0.9 | 1 | 0.9 | 1.1 | 0.9 | **1** |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3 | **1.5** | 1.4 | 1.4 | 1.6 | 1.3 | 1.2 | 1.2 | 1.4 | 1.3 | **1.2** |
| | | | 4 | **1.7** | 1.5 | 1.5 | 1.5 | 1.2 | 1.2 | 1.2 | 1.4 | 1.2 | **1.3** |
| | | | 5 | **1.8** | 1.4 | 1.5 | 1.6 | 1.5 | 1.7 | 1.5 | 1.7 | 1.5 | **1.6** |
| | | | 6 | **1.3** | 0.9 | 0.9 | 1.1 | 0.8 | 0.9 | 1 | 0.9 | 1.2 | **1** |
| | | | | | | | | | | | | | |
| SS bracket | SS wire | Coated ligature | 1 | **1** | 0.9 | 1 | 0.8 | 0.9 | 0.9 | 1 | 1.1 | 1 | **1** |
| | | | 2 | **1.4** | 1.3 | 1.3 | 1.4 | 1.4 | 1.5 | 1.3 | 1.3 | 1.4 | **1.4** |
| | | | 3 | **1.4** | 1.4 | 1.4 | 1.4 | 1.5 | 1.6 | 1.5 | 1.5 | 1.4 | **1.3** |
| | | | 4 | **1.5** | 1.4 | 1.4 | 1.4 | 1.1 | 1.2 | 1.2 | 1.3 | 1.5 | **1.3** |
| | | | 5 | **1.4** | 1.2 | 1.1 | 1.2 | 1.1 | 1.1 | 1 | 1.1 | 1.2 | **1.1** |
| | | | 6 | **1.4** | 1.3 | 1.4 | 1.5 | 1.3 | 1.3 | 1.2 | 1.3 | 1.2 | **1.3** |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | |
| SS bracket | Coated wire | Elastomeric ligature | 1 | **4.3** | 4.3 | 2.7 | 3.1 | 3.6 | 3.2 | 3.2 | 3.3 | 3.6 | **3.4** |
| | | | 2 | **4.1** | 3.8 | 2.7 | 2.7 | 3.5 | 2.7 | 2.6 | 2.6 | 3.4 | **3** |
| | | | 3 | **7.6** | 7.2 | 6.7 | 7.6 | 6.8 | 6.8 | 6.7 | 5.6 | 5.6 | **6.6** |
| | | | 4 | **4.3** | 4.5 | 4.4 | 4.9 | 4.7 | 4.7 | 4.1 | 5.3 | 4.4 | **4.6** |
| | | | 5 | **3.7** | 2.5 | 2.7 | 2.7 | 2.8 | 2.6 | 2.6 | 2.6 | 3 | **2.7** |
| | | | 6 | **3.2** | 3.1 | 2.9 | 3 | 3.1 | 3.1 | 3 | 3.1 | 3 | **3** |
| | | | | | | | | | | | | | |
| SS bracket | Coated wire | SS ligature | 1 | **3.9** | 3.6 | 3.9 | 3.3 | 3.4 | 3.2 | 3.3 | 3.5 | 3.5 | **3.4** |
| | | | 2 | **2.2** | 1.7 | 1.7 | 1.8 | 2.2 | 2.2 | 2.1 | 2 | 2.2 | **2** |
| | | | 3 | **2.3** | 1.8 | 1.8 | 2.2 | 2.2 | 2.4 | 2.2 | 2.2 | 2.5 | **2.2** |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 4 | **2.4** | 2.4 | 2.9 | 2.1 | 2.2 | 2.3 | 2.4 | 2.8 | 2 | **2.4** |
| | | | 5 | **5.6** | 2.4 | 2.4 | 2.9 | 2.8 | 3 | 4.5 | 3.6 | 3 | **3.1** |
| | | | 6 | **2.9** | 1.6 | 1.9 | 1.9 | 2.1 | 2 | 2 | 2 | 1.5 | **1.9** |
| | | | | | | | | | | | | | |
| SS brac ket | Coat ed wire | Coated ligature | 1 | **2.9** | 2 | 1.1 | 1 | 1 | 1.1 | 1.2 | 1.3 | 1.2 | **1.2** |
| | | | 2 | **3.1** | 1.7 | 1.4 | 1.6 | 1.5 | 1.6 | 1.7 | 1.4 | 1.4 | **1.7** |
| | | | 3 | **3.3** | 2.2 | 2.4 | 2.7 | 2 | 2.5 | 2 | 1.7 | 1.5 | **2.1** |
| | | | 4 | **1.7** | 1.6 | 1.7 | 2.1 | 2.1 | 1.9 | 2.4 | 1.6 | 1.5 | **1.9** |
| | | | 5 | **1.4** | 1.3 | 1.5 | 1.6 | 1.9 | 1.9 | 2.4 | 2.6 | 1.7 | **1.9** |
| | | | 6 | **2** | 1.3 | 1.1 | 1.9 | 1.8 | 1.7 | 2 | 2.5 | 2 | **1.8** |