

12-2011

Effect of Toothbrush Abrasion on Frictional Resistance of Aesthetic Orthodontic Archwires

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<http://dx.doi.org/10.34917/3400219>

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Effect of Toothbrush Abrasion on Frictional Resistance of Aesthetic Orthodontic Archwires

by

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A thesis submitted in partial fulfillment of the requirements for the

Master of Science in Oral Biology

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December 2011**

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THE GRADUATE COLLEGE

We recommend the thesis prepared under our supervision by

Stephen Alexander Yamodis

entitled

Effect of Toothbrush Abrasion on Frictional Resistance of Aesthetic Orthodontic Archwires

be accepted in partial fulfillment of the requirements for the degree of

Master of Science in Oral Biology

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December 2011

ABSTRACT

Effect of Toothbrush Abrasion on Frictional Resistance of Aesthetic Orthodontic Archwires
by

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Introduction: Fixed orthodontic appliances (braces) are one of the most widely used appliances to correct malocclusion, however many patients prefer less metal display. To meet this demand more esthetically pleasing brackets and archwires have been developed. These esthetic components are often clear, white or tooth colored. Coatings of various types are commonly used to produce an esthetic archwire. However, these coating materials tend to wear and degrade, which may cause binding and increased resistance to friction, thereby potentially reducing the efficiency of tooth movement. Therefore, *in vitro* testing of tooth brush abrasion on frictional resistance of various aesthetic archwires was tested. **Methods:** Frictional resistance of epoxy, palladium and polymer coated archwires were tested relative to uncoated archwires (controls). Nickel titanium archwires of size (0.016-in, 0.018-in, 0.017×0.025 -in, 0.019×0.025 -in) with these coatings were tested. Testing was also performed on stainless steel archwire sizes (0.018-in, 0.017×0.025 -in, and 0.019×0.025 -in) with epoxy and polymer coatings. Epoxy and polymer coated archwires as well as the uncoated archwires were provided by G&H Wire, Greenwood, IN., while palladium coated archwires were provided by Jin

Sung Co., Gyeonggi-Do, Korea. Standard edgewise twin brackets (MBT) 0.022×0.028 -in (American Orthodontics, Sheboygan, WI) were used to test each wire. Frictional resistance was tested using a United testing machine (United Calibration Corp., Huntington beach, CA) with a speed of 0.5 inches per minute, and testing period of two minutes. A 25 lb. load cell (Transducer Techniques, Temecula, CA) was mounted on the United testing machine. Kinetic frictional resistance values were recorded over a marked 0.5 inch span on each sample. **Results:** With the exception of one of the coated NiTi wires (epoxy 0.016-in), all coated NiTi wires exhibited a lower kinetic frictional resistance compared to the uncoated controls. All NiTi palladium coated wires were significantly ($P < 0.05$) lower in frictional resistance compared to the uncoated controls. With the exception of epoxy 0.017-in \times 0.025-in, all of the coated stainless steel wires exhibited an increase in force levels compared to the uncoated controls. The polymer group force levels were significantly higher ($P < 0.05$) for 0.017-in \times 0.025-in and 0.019-in \times 0.025-in while the epoxy group was significantly higher ($P < 0.05$) for the .018-in wire size. Toothbrush abrasion did not affect the frictional resistance of uncoated stainless steel but decreased frictional resistance for all but one (0.016-in) uncoated nickel titanium archwires although this decrease was not significant. **Conclusions:** Coated stainless steel archwires exhibited an increase in frictional resistance compared to uncoated stainless steel archwires, while coated nickel-titanium archwires exhibited a decrease in frictional resistance compared to uncoated nickel-titanium archwires. After eight minutes of abrasion there was an increased frictional resistance of palladium coated archwires and decreased frictional resistance of epoxy and polymer coated archwires.

ACKNOWLEDGEMENTS

I would like to thank Dr. James Mah and Dr. Brendan O'Toole for accepting the positions of Co-Chairperson for my advisory committee. Without their guidance and instruction this project would have never been possible. Dr. Mah and Dr. O'Toole are great leaders in their respective fields and it has been a pleasure working with them. They have both inspired me to achieve a higher level of success in my academic as well as professional pursuits. I would also like to thank Dr. Bob Martin for his willingness to serve on my committee. He is an inspiration by example, always bringing a positive energy and outlook to every endeavor. I would like to thank Dr. Mohamed Trabia for serving as my graduate college representative, his knowledge and advice has been tremendously helpful. I would like to thank Dr. Marcia Ditmyer for her help and guidance in collecting and compiling my statistical analysis. I would also like to thank Adam Kessler whose participation and dedication was extremely important to the completion of this project. Adam is a very intelligent and diligent person who has great knowledge of the machinery and data collection procedures used in this research project. I would also like to thank Jeremy Manuele, a current dental student who was interested in participating in a research project. I would also like to thank Drs. Happy Ghag and Sarika Anand for participating in the project. I would like to thank my wife Dr. Nadia Groves for her undying devotion and dedication of my academic pursuits as well as my daughter Sophia for being my inspiration to live every day to the fullest.

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1.0 INTRODUCTION

Crowded, irregular, and protruding teeth have been a problem for some individuals since early civilization. Archeological records indicate attempts at tooth movement date back to the Egyptians. Modern orthodontics generally includes the last 100 years with pioneers such as Norman Kingsley and Edward Angle. The specialty has since continued to advance with improvements in treatment armamentarium and technology. For many years modern treatment required the use of bands on all the teeth in addition to stainless steel archwires, which resulted in a prominent display of metal. This was not generally well perceived by the public, and the need to improve the esthetics for orthodontic appliances at the time was evident. With efforts to reduce metal display, a significant advancement was the development of bonded brackets in the late 1970's, which eliminated the use of conventional bands, particularly on the anterior teeth. In the 1990's clear or tooth colored brackets became a popular and well accepted appliance among providers and patients.

Today, there is great public interest in esthetic appliances. Esthetic appliances such as clear thermoformed aligners and ceramic brackets have made orthodontic treatment more acceptable to many patients. One of the most recent developments is esthetic archwire coatings. Within the last ten years there have been numerous archwires

produced with different types of coatings over the wire to make it appear more tooth colored. Durability, cost, effect on frictional resistance to sliding, access, and awareness are all contributing factors to the limited use of coated archwires. There are a small number of material property studies on these archwires however most of these have dealt with the effects of the coatings on the elasticity of nickel titanium samples. No published studies on the effects of tooth brush abrasion and frictional resistance on these coated archwires were available at the time of this experiment.

1.1 PURPOSE OF THE STUDY

The purpose of this research project is to 1) investigate if there is a significant difference ($p < 0.05$) in frictional resistance with three types of coated archwires available, compared to the traditionally used (non-coated) archwires, and 2) investigate if there is a significant difference ($p < 0.05$) in frictional resistance when comparing the three different types of coated archwires after toothbrush abrasion simulations of two, four and eight minutes. The wire characteristic tested in this study was frictional resistance before and after toothbrush abrasion. Frictional resistance was measured using a United testing machine in a tensile test equipped with a 25 lb. load cell.

1.2 SPECIFIC AIMS

Specific Aim 1: To measure frictional resistance of three different types of coated archwires (epoxy, palladium, and polymer) compared to uncoated archwires (stainless steel and nickel titanium) in vitro.

Null Hypothesis 1: There is no significant difference ($p < 0.05$) in frictional resistance between coated archwires and uncoated archwires.

Specific Aim 2: To measure the frictional resistance of three types of coated archwires (epoxy, palladium, and polymer) archwires after two, four and eight minutes of toothbrush abrasion compared to coated archwires with no abrasion in vitro.

Null Hypothesis 2: There is no significant difference ($p < 0.05$) in frictional resistance between an abraded coated archwire and a coated archwire with no abrasion.

Specific Aim 3: To measure the frictional resistance among three types of coated archwires (epoxy, palladium, and polymer) after two, four, and eight minutes of tooth brush abrasion in vitro.

Null Hypothesis 3: There is no significant difference ($p < 0.05$) in frictional resistance between the three types of coated archwires tested after two, four or eight minutes of toothbrush abrasion.

1.3 DEFINITION OF TERMS

Coated Archwire: An orthodontic archwire that is coated to appear tooth colored.

Control Archwire: Uncoated archwire.

Epoxy Coating: An esthetic archwire with an epoxy coating.

Esthetic Archwire: Coated archwire.

Lbf: Pounds of Force.

Length Conversions: 1 inch = 25.4 mm.

Force Conversions: 1 pound of force = 453 grams of force

Nickel Titanium (NiTi): One of the wire types to be tested.

Palladium Coating: An esthetic archwire with a palladium coating.

Polymer Coating: An esthetic archwire with a polymer coating.

Stainless Steel (SS): One of the wire types to be tested

Test Area: Area of wire where the recorded data for kinetic friction is collected and where toothbrush abrasion takes place.

Traditional Arch Wire: Uncoated orthodontic arch wire.

Toothbrush Abrasion: A two minute, four minute or eight minute cycle of brushing on a specified area on a wire.

Wire Types: A particular size of wire and material composition, either Nickel Titanium (NiTi) or Stainless Steel (SS).

1.4 LIMITATIONS OF THE STUDY

The toothbrush abrasion accounted for only one style (ultrasonic) of brushing and only one type of toothbrush (Phillips sonicare 6950, Snoqualmie, WA) and brush head (Pro Results Standard, Phillips sonicare, Snoqualmie, WA). The abrasion jig may have allowed some degree of movement of the toothbrush which could then affect depth of contact of the bristles.

Coating thickness could vary slightly within the same wire size and coating type due to manufacturer tolerances. Depending on the wire size and type tested this difference could affect the resultant force levels. The epoxy coated samples are 0.002" smaller in wire diameter than the polymer or palladium coated samples for a given wire

size. This has been shown to decrease the force levels exerted in a two point bending test for this coating and may affect force levels for a given wire size.

This experiment design did not reflect the dynamic response of tooth movement *in vivo*. As treatment progresses and the brackets align, the relative amount of archwire-bracket binding changes. During the initial stages of treatment, involving considerable archwire deflections for alignment and leveling, the amount of friction may not be constant; the binding is intermittently released as a result of the mobility of the teeth, the flexure of the archwire, and the yielding of ligatures. This study measured the frictional component of resistance to sliding between the archwire and the brackets during continuous binding, and did not allow for minute movements during occlusion and function which may release some of the binding.

Ligation of the wire samples to the testing jig was done using new alastic ties (Ormco 120, Orange, CA) for each wire sample. Manufacturer tolerances may have allowed for slight variations in thickness and chemical impurities which could affect the force of ligation and the force levels of frictional resistance.

While every effort was made to keep all observations during data collection as reliable as possible, it should be noted that the role of human error could not be eliminated completely. All wires were attempted to be ligated with the same orientation but there may have been slight variations due to operator error.

One testing jig was used for all archwire samples. After repeated uses the stainless steel brackets can show signs of notching and increase binding which lead to an increase in force values for samples tested at the end of the experiment compared to the

samples tested early in the experiment. This could then have increased the frictional resistance of the system as found Kapur et al. 1999 in a similar study.

There were no stainless steel archwires with a palladium coating available for testing.

2.0 LITERATURE REVIEW

2.1 HISTORY OF ORTHODONTIC ARCH WIRES

The precursor of the orthodontic arch wire, used in the late 1800's was the "arch bow" (Nikolai 1997), which consisted of a nickel-silver or a platinum-gold alloy. Its main drawback was its inability to perform individual tooth movements or leveling processes due to the stiffness associated with its cross sectional size that ranged from 0.032 to 0.036 inches (Nikolai 1997).

The introduction of stainless steel into the orthodontic community in the 1950's made the precious metal alloys obsolete even before the price increase in the 1970's made them prohibitively expensive (Kusy 2002).

Stainless steel's inherent characteristics rendered it far superior to the precious metal alloys, and replaced their use in orthodontics specifically due to its considerably better strength and springiness with equivalent corrosion resistance. Stainless steel's ability to resist corrosion results from its relatively high chromium content. A typical formulation for orthodontic use has 18% chromium and 8% nickel, thus this material is referred to as 18-8 stainless steel, (Kusy 1997).

Stainless steel wires can be utilized for many different orthodontic treatment applications. Manufacturers can vary the amount of cold working and annealing during its production which then allow for a broad spectrum of clinically useful wire bends and bio-mechanics. Steel is softened by annealing and hardened by cold working. Completely annealed stainless steel wires are soft and highly formable. Ligature wire used to tie orthodontic archwires into brackets is a completely annealed stainless steel wire. The trade-off that exists for the provider is as a stainless steel archwire is hardened by partial annealing, yield strength is increased but the formability is decreased. Orthodontic stainless steel wires are usually referred to as a regular grade and can be manipulated without fracture for most treatment procedures. However, if the applied strain is greater than the proportional limit plastic deformation will occur and if the failure point is exceeded, the wire will break.

After stainless steel, the first of the nickel titanium alloys, Nitinol was marketed in a stabilized martensitic form in the late 1970's. This wire offered good strength and springiness but poor formability. In the 1980's a "superelastic" property inherent to austenitic NiTi was introduced. . These wires were termed "superelastic," in part because elastic limit strains of these alloys in tension at oral temperature were four to five times that of orthodontic stainless steel, but also because of the "plateau" (nearly constant strain) segments within the deactivation portions of their elastic stress-strain cycles. Superelastic wires are widely accepted by practitioners almost a decade after their introduction. Researchers continue to investigate their multiple strain-energy and temperature-dependent characteristics and potential disadvantages of these alloys, (Nikolai 1997). Most recently copper NiTi archwires have been manufactured which

offer the superelastic properties of austenitic NiTi and a smaller range of thermal activation to more closely represent those temperatures of the oral cavity. A Beta-titanium alloy (TMA) was also introduced in the mid 1980's. This archwire is comprised of an alloy with titanium and molybdenum. TMA has a wide elastic range, ductility, and characteristics comparable to those of orthodontic stainless steel wires, but exhibited only approximately 40% of the steel's material stiffness.

As technology advances and the demand goes up more research is being emphasized on producing an efficient and aesthetic archwire. Currently, aesthetic archwires are made by using a traditional archwire and applying a tooth colored coating but these may be replaced by a completely aesthetic material at some point in the near future. There are resin fibers with better strength and springiness than non-superelastic archwires but there are none to date that can offer superelastic properties. Some of these resin fiber archwires are currently being used in select orthodontic therapies if the situation is appropriate. One of the latest and more exciting developments in this regard is a translucent all-polymeric wire with high springback and high ductility (Goldberg and Burstone, 2007; Burstone et al., 2010).

Past investigations of the frictional properties of composite wires against several orthodontic brackets showed that reinforcement fibers in the wires were subject to considerable wear from abrasive forces, and subsequently released glass fibers (Zufall 2000). This release of glass fibers within the oral cavity was considered unacceptable, and a polymeric surface coating was suggested as a potential remedy. The prerequisites for this coating material were that it be easily applicable in thin layers, be wear resistant, and have low frictional characteristics (Elayyan 2010).

Nonmetallic wires can be very flexible and highly resilient as a result of their inherent properties, and a metallic component is at times required to add a component of ductility (Goldberg 2010). Without any metallic components, concerns related to surface hardness, roughness, and material continuity arise.

The titanium alloy wires, in comparison to stainless steel wires, are less conducive to sliding mechanics as those of stainless steel. Recently, wire surfaces have been subjected to ion bombardment in an effort to enhance certain characteristics such as hardness and smoothness (Kusy 2000).

Wire suppliers have recently been experimenting with coatings on their stainless steel and nickel titanium alloy archwires to help improve esthetics by creating a wire that will match the color of tooth. Some of the more common complaints of providers and patients are that these coatings will crack, peel off and or increase roughness. Most of the coatings are plastic resin materials such as synthetic fluorine-containing resin or epoxy resin composed mainly of polytetrafluoroethylene to simulate tooth color. For both the epoxy resin and the polymer samples tested in this experiment, the process of applying these layers includes the use of clean compressed air as a transport medium for the atomized polymer particles to coat the wire, which is further heat treated in a chamber furnace, (Husmann *et al.* 2002). The palladium samples are first prepared by removing oxides on the archwire surfaces by reducing agents such as strong acid salts. The archwires are then electroplated. The aim of this study was to test a sample of epoxy coated, polymer coated and palladium coated wires to determine their effects on frictional resistance compared to an uncoated archwire.

2.2 CLINICALLY SIGNIFICANT CHARACTERISTICS OF ORTHODONTIC ARCHWIRES

Several characteristics of orthodontic wires are considered desirable for optimum performance during treatment. These include a large springback, low stiffness, high formability, high stored energy, biocompatibility and environmental stability, low surface friction, and the capability to be welded or soldered to auxiliaries and attachments (Kapila 1989). Although no single wire can possess all of these traits, the goal is to select a wire that will best meet the requirements of a particular phase of treatment.

Springback is referred to as maximum elastic deflection, maximum flexibility, range of activation, range of deflection, or working range. It is related to the ratio of yield strength to the modulus of elasticity of the material (YS/E). Higher springback values provide the ability to apply large activations with a resultant increase in working time of the appliance. This, in turn, implies that fewer arch wire changes or adjustments will be required. Springback is also a measure of how far a wire can be deflected without causing permanent deformation or exceeding the limits of the material. Stiffness or load deflection rate is the force magnitude delivered by an appliance and is proportional to the modulus of elasticity (E). Low stiffness or load deflection rates provide (1) the ability to apply lower forces, (2) a more constant force as the appliance experiences deactivation, and (3) greater ease and accuracy in applying a given force.

A high formability provides the ability to bend a wire into desired configurations such as loops, coils, and stops without fracturing the wire. Modulus of resilience or stored energy (M) represents the work available to move teeth. Biocompatibility and environmental stability includes resistance to corrosion and tissue tolerance to elements

in the wire. Environmental stability ensures the maintenance of desirable properties of the wire for extended periods of time after manufacture. This, in turn, ensures a predictable behavior of the wire when it is used. Joinability is the ability to attach auxiliaries to orthodontic wires by welding or soldering provides an additional advantage when incorporating modifications to the appliance. Space closure and canine retraction in continuous arch wire techniques involve a relative motion of bracket over wire. Excessive amounts of bracket/wire friction may result in loss of anchorage or binding, which would consequently lead to little or no tooth movement. The preferred wire material to most effectively facilitate tooth movement would be one that produces the least amount of friction at the bracket/wire interface (Kapila and Sachdeva 1989).

2.3 MECHANICAL PROPERTIES AND THEIR CLINICAL IMPLICATIONS

Controlled tooth movement in all three planes of space using a fixed orthodontic appliance consisting of a bracket, archwire and ligature is the goal for all archwires. A majority of orthodontic archwires, basically all except those exhibiting superelastic properties, adhere to the principles of Hooke's law. The tensile stress-strain plot is linear virtually to the elastic limit, and the deactivation/unloading plot is essentially a straight line with a slope equal to the modulus of elasticity, regardless of the maximum activation state beneath the fracture point (Nikolai 1997).

With these mechanical properties and wire characteristics in mind, the current study focuses on wires most frequently encountered in current orthodontic therapies. This

study narrows the focus to the frictional resistance of these more aesthetic archwires. A brief background on friction as it relates to orthodontics is first required.

2.4 REVIEW OF FRICTIONAL RESISTANCE RELATED TO THE WIRE/BRACKET INTERFACE

Friction in orthodontic treatment mechanics has attracted considerable attention in recent years. Appliance manufactures have battled over whose bracket or system has the least friction. Treatment principles and modalities have been developed to account for the effects of friction on tooth movement and biological response. In spite of the number of studies related to this subject, however, there is little agreement on how best to measure friction and determine its clinical significance, (Swartz 2007). The first law of friction states that the frictional force is proportional to the applied load (N) by a constant, the coefficient of friction (μ) ($F = \mu * N$). The coefficient of friction depends on the material's relative roughness. Surface roughness is a characteristic of the material itself, its shelf life, and the manufacturing processes (polishing and heat treatment), (Doshi 2011). When one moving object contacts another, friction at their interface produces resistance to the direction of movement. The frictional force is proportional to the force with which the contacting surfaces are pressed together, and is affected by the nature of the surface at the interface (rough or smooth, chemically reactive or passive, whether or not it is modified by lubricants, etc.). Friction is independent of the apparent area of contact. This is because all surfaces, no matter how smooth, have irregularities that are large on a molecular scale, and real contact occurs only at a limited number of small spots at the peaks of the surface irregularities. These spots, called asperities, carry the load between

the two surfaces. Even under light loads, local pressure at the asperities may cause appreciable plastic deformation of those small areas. Because of this, the true contact area is determined by the applied load.

While kinetic friction is defined as the force needed to keep an object in motion, static friction is defined as the force necessary to initiate movement. Static friction, the force between the archwire and the bracket, must be overcome to commence tooth movement. In an optimal bracket-wire combination, about 40g of friction must be included in the force applied to the tooth to initiate movement. The amount of frictional force generated at the bracket-wire interface has been minimized in recent years with newer bracket designs and manufacturing techniques (Burrow 2009).

When a tangential force is applied to cause one material to slide past the other, the junctions begin to shear. The coefficient of friction then is proportional to the shear strength of the junctions and is inversely proportional to the yield strength of the materials. At low sliding speeds, a “stick-slip” phenomenon may occur as enough force builds up to shear the junctions causing a jump to occur. The surfaces then stick again until enough force builds up to break them (Proffit 2000). There are two additional factors that can affect resistance to sliding. The first is the interlocking of surface irregularities, which obviously becomes more important when the asperities are large or pointed. And the second is the extent to which asperities on a harder material plow into the surface of a softer one. The total frictional resistance will be the sum of three components: (1) the force necessary to shear all junctions, (2) the resistance caused by the interlocking of roughness, and (3) the plowing component of the total friction force.

In practice, if the two materials are relatively smooth and not greatly dissimilar in hardness, friction is largely determined by the shearing component (Proffit 2000).

Frictional resistance between archwires and brackets can be reduced by modifying any or all of the major factors discussed above, but it cannot be totally eliminated. It is possible in the laboratory to measure the actual friction between various wires and brackets and then compare that magnitude of frictional resistance with the force required to produce actual tooth movement (Proffit 2000).

Many factors which influence friction have been investigated; these include wire alloy composition and dimensions, bracket material and width, as well as the test conditions, including method of ligation. Wire alloy composition is significant with stainless steel showing the least friction increasing through cobalt-chromium, nickel-titanium and beta-titanium (Kusy and Whitley, 1990). Rectangular wires tend to increase frictional resistance more than round wires (Frank and Nikolai, 1980), and there is more friction with large diameter wires compared to small wires (Ho and West, 1991). Furthermore, friction is also increased with increasing cross section of the guiding archwire, with the vertical wire cross section being crucial to frictional behavior (Husmann 2002). Second order angulation has also been found to be a critical factor in determining frictional resistance (Andreasen and Quevedo, 1970; Tidy, 1989). This binding of the wire against the corners of the bracket can create notching which will temporarily stop movement (Burrow 2009).

Investigations into bracket material have found that both plastic and ceramic brackets consistently show higher frictional resistance than stainless steel brackets (Angolkar *et al.*, 1990). Studies on the influences of bracket width on friction gave

inconsistent results which may be due to variation in levels of second order angulation (Frank and Nikolai, 1980; Andreasen and Quevedo, 1970; Peterson *et al.*, 1982; Tidy 1989). It has been demonstrated by Kapur *et al.* 1999 that there is a possibility of an increase in frictional resistance due to bracket wear.

Differences between testing in dry and wet conditions have provided conflicting and inconclusive results with respect to the effects of lubrication on frictional resistance. Andreasen and Quevedo, 1970 reported that there was no effect of lubrication on frictional resistance. Stannard *et al.*, 1986 reported an increase in frictional resistance with lubrication, while Ireland *et al.*, 1991 reported a decrease. The difference between artificial saliva and water in friction testing is negligible (Baker *et al.*, 1987). The third law of friction states that the coefficient of friction is independent of velocity is not always correct and may be modified by the surface characteristics of the various alloys. Although cold-welding may occur with beta-titanium, the sliding velocity does not appear to affect the coefficient of friction in stainless steel (Kapila *et al.*, 1990).

This study had to take into account three significant influences on frictional resistance. A conscious effort was made to hold two of the three contributing factors constant in all experimental groups, surface quality of brackets and ligation of the wire to the bracket. The third significant influence, the surface of the wire, was the main interest of this study. Other factors that can affect frictional resistance include saliva, archwire dimension, angulation of the wire to the bracket, and mode of ligation (Ehsani 2009).

The concept that surface qualities are an important variable in determining friction has been emphasized by experiments in the late 1980's with titanium wires against both ceramic and plastic brackets. When NiTi wires were first introduced,

manufacturers claimed they had an inherently smooth surface when compared to stainless steel wires. As a result, they also claimed that this allowed less interlocking of asperities, and thereby less friction while sliding a tooth along a NiTi wire. Numerous studies proved this to be erroneous, the surface of NiTi is in fact rougher (due to surface defects, not the quality of polishing) than that of beta-Titanium, which in turn is rougher than stainless steel. However, even with an increase of surface roughness which was thought to directly increase friction, there is little or no correlation between coefficients of friction and surface roughness with respect to orthodontic archwires (Kusy 1997). Specifically, interlocking and plowing were not considered significant components in the total frictional resistance associated with an archwire. NiTi, although greater in surface roughness, was found to have a lower frictional resistance than beta-Titanium. It was further concluded that the titanium content of a wire was in fact the major determinant of frictional resistance. As the titanium content of an alloy increases, so does its frictional resistance. Beta-Titanium, which contains up to 80% titanium, has a higher coefficient of friction than NiTi, which contains 50% titanium. Both of these titanium alloys have a greater frictional resistance to sliding than stainless steel. (Kusy 1997). A possible solution to this problem is alteration of the surface of the titanium archwires using ion implantation. Ion implantation (with nitrogen, carbon, and other materials) has been done successfully with beta-Ti, and has been shown to improve characteristics of beta-Ti hip implants. In clinical orthodontics, however, implanted NiTi and beta-Ti wires have failed to show improved performance in initial alignment or sliding space closure. A possible explanation for this could be that friction is released when teeth move as bone bends during mastication.

Bracket surfaces are also important to consider when evaluating friction. Most modern orthodontic brackets are either cast or milled from stainless steel, and if properly polished have relatively smooth surfaces comparable with steel wires. Titanium brackets are now being used primarily because of their better biocompatibility as stainless steel wires and appliances were contraindicated in certain patients with a nickel allergy. Although the number of patients with a nickel allergy has increased, it has been reported that not all individuals with a nickel allergy exhibit a mucosal reaction to nickel. As the surface properties of titanium brackets can be considered similar to those of titanium archwires, polishing the interior bracket slots presents a challenge and can cause these critical areas to be rougher than archwires. Sliding with titanium brackets, therefore, may be problematic, particularly if titanium archwires are also used.

Ceramic brackets became quite popular in the 1980's because of their improved esthetics, but problems related to frictional resistance with respect to sliding have limited their use. The rough, hard ceramic material can penetrate the surface of a steel wire during sliding, creating considerable resistance. To address concerns of frictional resistance while maintaining its esthetic benefits, ceramic brackets with metal slots were introduced.

Improvements with manufacturing and chemical make-ups have allowed composite brackets to be routinely offered to patients as a fixed appliance option. They have the advantages of being tooth colored and non-allergenic, and at least in theory, should have surface properties that would not be as troublesome as ceramics.

In contemporary orthodontics brackets are self -ligating or ligated with elastomeric modules or very thin stainless steel ties. The term “self-ligation” in

orthodontics implies that the orthodontic bracket has the ability to engage itself to the archwire and is therefore assumed to reduce friction by eliminating the ligation force. These bracket systems have a mechanical device built into the bracket to close off the edgewise slot. Two types of self- ligating (SL) brackets have been developed: an active bracket that contains a spring clip that presses against the arch wire, and a passive bracket that contains a SL clip that simply closes the slot without actively pressing against the archwire. With every SL bracket, whether it be active or passive, the movable part of the bracket, commonly referred to as the clip, is used to convert the slot into a tube (Ehsani 2009). Most of the studies done thus far have indicated that self- ligating brackets reduce friction (Berger, 1990; Sims et al., 1993) when engaged with a small diameter round archwire. Bracket selection undeniably plays a role in frictional resistance. To minimize its effects on the results obtained from this study, brackets were kept consistent throughout the experiments for all wires. The goal was to investigate a single variable, which was the archwire.

2.41 LIGATION

Ligation with steel ties can lead to higher frictional forces as a range of ligating forces may be used by different operators (Riley et.al., 1979). Sims et al. (1993) studied two methods of ligation with elastomeric ligatures; regular and a figure-of-eight pattern. They found the figure-of-eight pattern greatly increased the friction relative to the conventional ties. Tselepis et al. (1994) found no statistically significant difference on frictional forces when using different elastic ligature rings.

2.42 FORCE OF CONTACT

The amount of force between the archwire and the bracket strongly influences the amount of friction, and is determined by two factors. First, if a tooth is pulled along an archwire, it will tip until the corners of the bracket contact the archwire generating a moment that prevents further tipping. Any archwire that is smaller than the bracket initially must cross the bracket at an angle. As this angle is increased, the initial moment is increased, and force between the archwire and the bracket is increased. Frictional resistance will increase rapidly as the angle between the bracket and the archwire increases even slightly. As a result, elastic properties of the wire influence friction, especially as bracket angulation increases. Flexible archwires will bend, reducing the angle between the archwire and the bracket. Another factor that will reduce frictional resistance is the width of the bracket, it will be easier to generate the moments needed to control root position with a wide bracket because the wider the bracket, the smaller the force needed at its edges to generate any necessary movement.

A second factor that influences frictional resistance involves the ligature that holds the wire in place. With respect to frictional resistance, the force generated by ligature ties is significant, and outweighs the force related to bracket width. This supports the theory that sliding has better results when archwires are not held tightly into their brackets. Passive self-ligating brackets have a considerable reduction in friction allowing more effective sliding and subsequently improved anchorage control.

2.43 MAGNITUDE OF FRICTION

The force required to overcome friction between archwire and brackets is often underestimated. It should be noted that even in a passive configuration such as a 0.014-in wire in a 0.022×0.028-in slot bracket, there is measurable friction. The minimal frictional resistance to sliding a single bracket along an archwire is approximately 100 grams. Specifically, for example, if a canine tooth is required to slide along an archwire to close space following an extraction, one can estimate that an additional 100 gm of force would be required to overcome friction. The total force, therefore, required to slide the tooth is twice that which may have originally been anticipated. The frictional resistance can be reduced, but not eliminated, by replacing the ligature tie with a self-ligating clip to ensure the archwire is held in place loosely.

Most of the research efforts to understand the factors that influence frictional resistance in orthodontics when considering sliding mechanics have been focused on bracket width, archwire material, archwire size, second-order angulation, ligation type and technique, effects of saliva, and inter-bracket distance (Stefanos 2010). According to Pizzoni et al, experimental setups to determine the effects of the factors mentioned above can be divided into 4 main groups: (1) archwires sliding through contact flats; (2) archwires sliding through brackets parallel to the bracket slot; (3) archwires sliding through brackets with different second- and third-order angulations; and (4) brackets submitted to a force with a certain degree of tipping allowed.

2.5 SUMMARY OF CURRENT FINDINGS FOR COATED ARCHWIRES

Coating or refining the wire surface has an influence on frictional behavior. In comparison to an uncoated wire, coating creates a modified surface which can influence not only friction but also the esthetics, corrosive properties, and mechanical durability of the wires (Husmann 2002). When the frictional behavior of plastic-coated archwires was compared with non-coated reference wires by the same manufacturer, plastic coatings were found to have a significant effect in decreasing friction (Elyyan 2010). Although capable of decreasing friction, Proffit 2000, described this coat as “undurable”. Kusy 2002 also found that, when coated, the colored wires were routinely damaged within three weeks of their use in vivo from forces of mastication as well as the activity of enzymes found in the oral cavity (Lim *et al.*, 1994, Postlethwaite, 1992). Other authors also encountered difficulties with these coated archwires, claiming that the color was unstable, and changed over time. They also reported that the coating separated while in the mouth causing the underlying metal to become exposed. Despite the revelation of their durability problems, as well as a lack of studies examining their mechanical properties, these coated wires continue to be marketed and used in clinical practices (Elayyan 2010). The majority of research done thus far on coated archwires has involved NiTi archwire samples and has indicated a reduction in frictional resistance with coated archwires. In addition to reducing frictional resistance, Elayyan et al. 2010 also found that for 0.016-in and 0.018×0.025-in Epoxy coated nickel titanium (G&H) wires produced lower loading and unloading forces compared to uncoated wires of the same dimensions. When evaluating the the *ex vivo* surface, Elayyan *et al.*, 2008 found that

after 33 days, retrieved coated archwires displayed an increase in surface roughness. They also found that during the same 33 day period, 25% of the coating was lost and there was severe deterioration in the surface morphology as shown by optical and scanning electron microscopy.

3.0 METHODOLOGY

An experimental model reproducing a right buccal segment of the upper arch was used to assess kinetic friction produced by three different types of coated archwires and the uncoated control archwires.

3.1 STUDY DESIGN

This study was conducted using an experimental design with a control group consisting of uncoated wires, and three treatment groups consisting of epoxy, polymer, or palladium coated archwires. Each of the coatings was tested on four NiTi archwires (0.016-in NiTi, 0.018-in NiTi, 0.017x0.025-in NiTi, and 0.019x0.025-in NiTi), and the epoxy and polymer coatings were tested on an additional three stainless steel archwires (0.018-in SS, 0.017x0.025-in SS, and 0.019x0.025-in SS). Samples for the palladium coating on stainless steel archwires were not available. For each archwire size in its respective group, 10 wire samples were used. The treatment groups and the control group then underwent 2, 4, and 8 minutes of tooth brush abrasion using a Phillips sonicare HX 6950 toothbrush and an abrasion testing jig (Figure 1). Frictional resistance was

measured for each wire sample before abrasion and after 2,4 and 8 minutes of abrasion. After 50 archwire tests, a baseline test was conducted using uncoated 0.016-in NiTi to determine if the testing jig or methodology had been compromised. 10 tests of this baseline archwire were collected. To detect any gross abrasion, scanning light microscopy (10/0.025 magnification) Vista Vision, 43300-538, VWR International was used to evaluate the archwires with the biggest frictional discrepancies after abrasion. These images were taken at (1280×960 resolution).

3.2 SAMPLE SELECTION AND SAMPLE SIZE

The epoxy coated and polymer coated archwires were manufactured by G&H Wire (Greenwood, IN.) According to the manufacturer, the epoxy coating is 0.002 inches in thickness. Thus, for any given epoxy coated wire the actual archwire diameter was 0.002 in smaller than its respective equivalent in the control group, as well as in the other treatment groups. The palladium coated archwires were manufactured by Jin Sung Co. (Korea).

Each treatment group and the control group were further divided into four subgroups. The first subgroup (A) was used to measure frictional resistance only (no abrasion). The second subgroup (B) was used to measure frictional resistance after 2 minutes of toothbrush abrasion. The third subgroup (C) was used to measure frictional resistance after 4 minutes of toothbrush abrasion. Finally, the fourth subgroup (D) was used to measure frictional resistance after 8 minutes of toothbrush abrasion. The locations on the

wires where toothbrush abrasion took place were consistent for all wires, as a specific toothbrush abrasion testing apparatus was used.

There were a total of 1000 tests with the following breakdown: There were seven different wires tested for the epoxy treatment group, the polymer treatment group and the control group. For each of these groups there were four subgroups, 10 samples for each subgroup totaling 280 wires tested for each group. There were four different wires (all NiTi) tested for the palladium treatment group, each with four subgroups and 10 samples of each subgroup, totaling 160 wires tested.

3.3 INSTRUMENTATION

To evaluate in vitro the effect of three types of coatings on the kinetic frictional resistance generated by orthodontic sliding mechanics under dry conditions a testing apparatus modeled after Chimenti *et al.* 2005 was used. An experimental model made to represent a buccal segment of an intraoral arch was used to assess the frictional forces produced by coated and non-coated archwires. The buccal segment consisted of six stainless steel brackets (Standard edgewise twin brackets, MBT, 0.022×0.028 -in American Orthodontics, Sheboygan, WI). A central incisor, a lateral incisor, a canine, a first premolar, a second premolar, as well as a molar tube affixed with epoxy to a metal strip, which was secured to a stabilization block. A section of $0.0215\text{-in} \times 0.028\text{-in}$ stainless steel wire was used to align the bracket slots and molar tube in a parallel fashion before being secured to the metal housing. The metal housing was then clamped and locked into position at the base of the United testing machine (United Calibration Corp.,

Huntington beach, CA). The distance between the brackets was set at 8 mm (Figure 2). The frictional resistance was registered by a 25 lb. load cell (Transducer Techniques, Temecula, CA), and the results were analyzed with Statistical Package for the Social Sciences (IBM, Armonk, NY). The load cell recorded the pounds of force (lbf.) opposing the motion of the wire through the 6 brackets of the buccal segment. The force applied to the wire was controlled using the United Testing Machine software, and was applied at a constant crosshead speed of (0.5) in/min. The force recorded was directly proportional to the friction coefficient between the archwire and the ligature, and the normal force exerted on the archwire by the ligature and bracket. In order to ensure that the archwire was the only variable contributing to changes in frictional resistance that were measured by the load cell, the type of bracket and the material used for the ligature were kept consistent. The load cell recorded the force once every second for the duration of the test. This force was registered by the cell, then calculated with a strain indicator (blue box), and finally recorded to a laptop using Microsoft Excel Software. Approximately 100 data points were recorded for each test, and each corresponded to a value of kinetic friction that was generated as a pre-marked section of wire passed completely through a bracket. Specifically, a distance of 0.57 inches (15 mm) was designated as the “test area” and represented the distance the wire needed to move to pass completely through one bracket. The marks designating “testing areas” were made at the same location for all wires, and the abraded areas were also included in the same “test areas”.



Figure 1 Toothbrush abrasion testing jig.

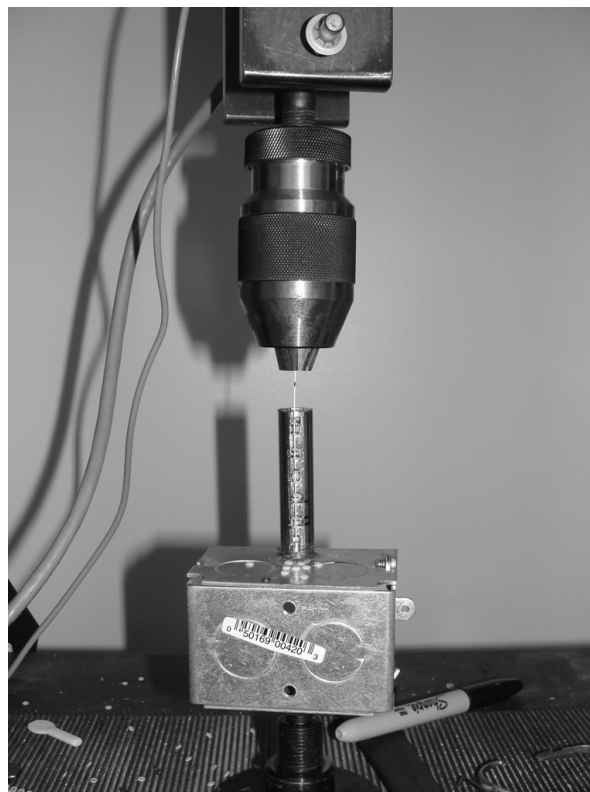


Figure 2 Frictional Resistance testing jig.

3.4 METHODS OF ANALYSIS

Sample size calculations for detecting 10% differences in these values suggested testing 10 archwires in each group. Two-way analysis of variance (ANOVA) was used to identify main effects on frictional resistance when comparing coated and non-coated wires, as well as the effects on frictional resistance with respect to different wire sizes. Multiple comparisons among treatment groups were made using Post Hoc Tests (Bonferroni). All statistical tests were undertaken assuming a level of significance where $P < 0.05$.

4.0 FINDINGS OF THE STUDY

All treatment groups (epoxy, polymer, and palladium) were tested on the following four NiTi wires: 0.016-in, 0.018-in, 0.017x0.025-in, and 0.019x0.025-in. The epoxy and polymer treatment groups were also tested on an additional three stainless steel wires in the following sizes: 0.018-in, 0.017x0.025-in and 0.019x0.025-in. In each treatment group 10 samples of every size and type of wire were tested. The wire samples were pulled at a speed of 0.5 inches per minute through the testing jig. The frictional resistance was measured in pounds of force (lbf.). The load cell values are reported to an estimated reliability of (0.025lbf). Table 1 lists the level of significance for the treatment groups according to wire size and abrasion times. Table 2 lists the average force values and standard error for each wire size and type.

All the non-coated wires were tested first for a baseline level of resistance (Figure 3). It can be seen from the graph that 0.018-in NiTi had the highest force levels at 1.87 lbf. From Figure 4 it can also be seen that for a given wire size the NiTi wire required a

greater force than its stainless steel counterpart, which is supported in theory by previous experimentation and research (Kusy and Whitley, 1990). The greatest difference was reported between the 0.018-in NiTi (1.87 lbf.) and the 0.018-in SS (0.71 lbf.) wires.

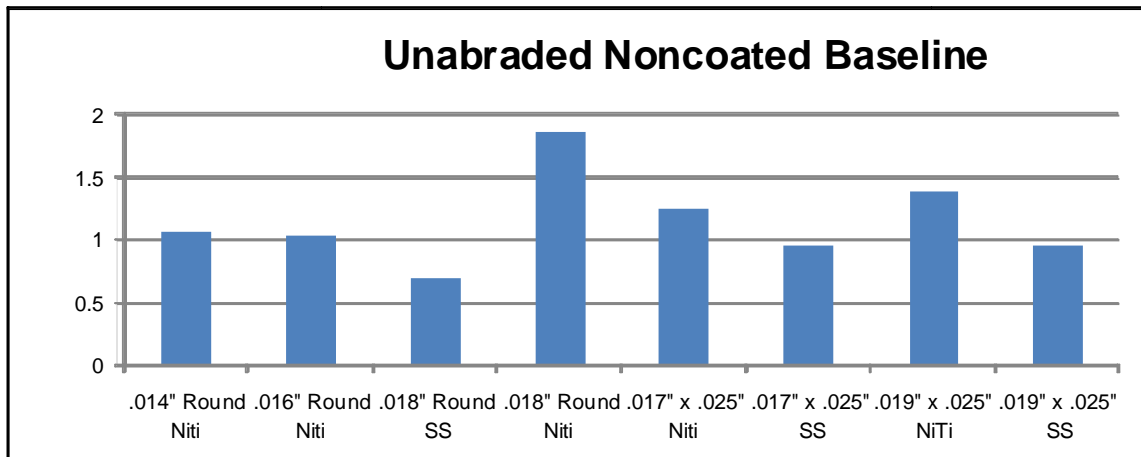


Figure 3 Mean frictional resistance values for non-coated wires with no abrasion.

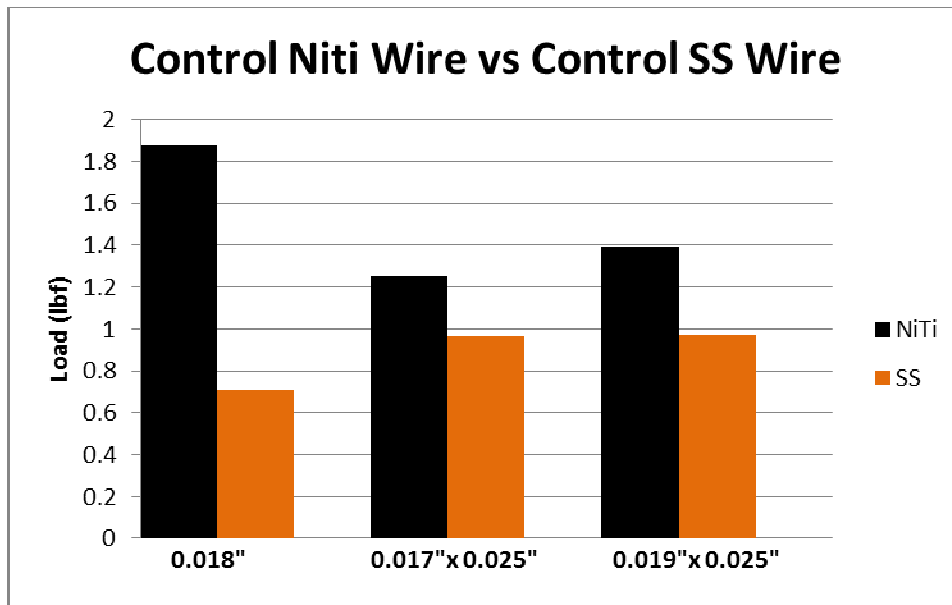


Figure 4 Mean frictional resistance values for control nickel-titanium and stainless steel wires.

4.1 SIGNIFICANT FINDINGS

Table 1

Statistical Comparisons Among the Different Types of Coatings

Time	Wire Size	Type of Coating	Mean	(SD)	Statistic
	.016NT	Control = no coating	1.04	0.22	27.94**
		Polycarbonate Coating	0.89	0.21	
		Epoxy Coating	1.46	0.22	
		Palladium Coating	0.7	0.12	
2	.016NT	Polycarbonate Coating	0.69	0.12	1.94
		Epoxy Coating	0.79	0.07	
		Palladium Coating	0.7	0.17	
4	.016NT	Polycarbonate Coating	0.76	0.12	25.24**
		Epoxy Coating	1.24	0.13	
		Palladium Coating	1	0.17	
8	.016NT	Polycarbonate Coating	0.83	0.11	43.36**
		Epoxy Coating	1.1	0.08	
		Palladium Coating	0.73	0.08	
	.018NT	Control = no coating	1.88	0.46	20.20**
		Polycarbonate Coating	1	0.22	
		Epoxy Coating	1.51	0.22	
		Palladium Coating	0.95	0.27	
2	.018NT	Polycarbonate Coating	0.79	0.4	6.00*
		Epoxy Coating	0.98	0.12	
		Palladium Coating	1.23	0.27	
4	.018NT	Polycarbonate Coating	0.93	0.21	4.56*

		Epoxy Coating	1.22	0.25	
		Palladium Coating	1.13	0.19	
8	.018NT	Polycarbonate Coating	0.91	0.16	2.21
		Epoxy Coating	1.01	0.09	
		Palladium Coating	1.04	0.19	
	.018 SS	Control = no coating	0.71	0.07	77.21**
		Polycarbonate Coating	0.96	0.17	
		Epoxy Coating	1.82	0.27	
2	.018SS	Polycarbonate Coating	0.88	0.12	1.98
		Epoxy Coating	0.97	0.17	
4	.018SS	Polycarbonate Coating	0.92	0.11	5.47*
		Epoxy Coating	1.07	0.19	
8	.018SS	Polycarbonate Coating	1.11	0.15	0.7
		Epoxy Coating	1.04	0.19	
	.017 x .025NT	Control = no coating	1.25	0.15	12.48**
		Polycarbonate Coating	1.28	0.12	
		Epoxy Coating	1.04	0.29	
		Palladium Coating	0.82	0.17	
2	.017 x .025NT	Polycarbonate Coating	1.06	0.16	1.99
		Epoxy Coating	1.02	0.13	
		Palladium Coating	1.22	0.36	
4	.017 x .025NT	Polycarbonate Coating	0.96	0.19	4.45*
		Epoxy Coating	0.86	0.09	
		Palladium Coating	1.08	0.19	
8	.017 x .025NT	Polycarbonate Coating	0.94	0.17	1.35
		Epoxy Coating	1.09	0.29	
		Palladium Coating	1.12	0.32	

	.017 x .025SS	Control = no coating	0.97	0.14	41.8**
		Polycarbonate Coating	1.34	0.12	
		Epoxy Coating	0.81	0.14	
2	.017 x .025SS	Polycarbonate Coating	1.3	0.3	4.82*
		Epoxy Coating	1.07	0.13	
4	.017 x .025SS	Polycarbonate Coating	1.14	0.17	0.528
		Epoxy Coating	1.07	0.24	
8	.017 x .025SS	Polycarbonate Coating	1.11	0.15	0.702
		Epoxy Coating	1.04	0.19	
	.019 x .025NT	Control = no coating	1.39	0.24	32.42**
		Polycarbonate Coating	1.46	0.1	
		Epoxy Coating	1.05	0.21	
		Palladium Coating	1.16	0.34	
2	.019 x .025NT	Polycarbonate Coating	1.35	0.1	6.73**
		Epoxy Coating	1.21	0.12	
		Palladium Coating	1.06	0.25	
4	.019 x .025NT	Polycarbonate Coating	1.06	0.16	0.75
		Epoxy Coating	1.06	0.16	
		Palladium Coating	1.14	0.18	
8	.019 x .025NT	Polycarbonate Coating	0.76	0.08	12.43**
		Epoxy Coating	1.1	0.22	
		Palladium Coating	0.9	0.13	
	.019 x .025SS	Control = no coating	0.97	0.13	4.35*
		Polycarbonate Coating	1.3	0.17	
		Epoxy Coating	1.17	0.37	
2	.019 x .025SS	Polycarbonate Coating	1.23	0.24	15.11*
		Epoxy Coating	0.88	0.15	

4	.019 x .025SS	Polycarbonate Coating	1.14	0.17	0.528
		Epoxy Coating	1.07	0.24	
8	.019 x .025SS	Polycarbonate Coating	1.07	0.12	0.331
		Epoxy Coating	1.04	0.17	

* P < 0.05, ** P < 0.01.

4.2 UNABRADED WIRES: COATED COMPARED TO UNCOATED

0.016 NiTi:

There was a significant ($p < 0.01$) lower force level (Figure 4) required to pull the palladium coated wire (0.69 lbf.) through the brackets compared to the uncoated control group (1.03 lbf.) indicating less frictional resistance with the palladium coated wire.

Table 1 illustrates that the force levels required for the epoxy coated treatment group (1.46 lbf.) were significant ($p < 0.01$) and were greater when compared to the uncoated control group (1.03 lbf.). Table 1 also shows a significant difference ($p < 0.01$) between the epoxy coated wire and the palladium coated wire. There was no significant difference between the uncoated control group and the polymer coated treatment group (1.03 lbf. and 0.88 lbf.) for this wire type and size.

0.018 NiTi:

There was a significant difference ($p < 0.01$) between the force levels required for both the palladium and polymer treatment groups, and those required for the uncoated control group (0.95 lbf. and 1.00 lbf. compared to 1.87 lbf.). There was also a significant difference ($p < 0.01$) when comparing the force levels required for the palladium and

polymer treatment groups with those of the epoxy treatment group (0.95 lbf. and 1.00 lbf. compared to 1.51 lbf.).

0.018 SS

There was a significant difference ($p < 0.01$) between the force levels (Figure 5) required for the epoxy treatment group (1.82 lbf.) and those required for the uncoated control group (0.71 lbf.) and the polymer treatment group (0.95 lbf.). There was no significant difference between the polymer treatment group and the uncoated control group.

0.017*0.025 NiTi

There was a significant difference ($p < 0.01$) between the force levels required for the palladium treatment group (0.81 lbf.) and those required by both the polymer treatment group (1.27 lbf.) and the uncoated control group (1.25 lbf.). The force required by the epoxy treatment group (1.04 lbf.) was less than that required by the control but was not significant.

0.017*0.025 SS

There was a significant difference ($p < 0.01$) between the force levels required by the epoxy treatment group (0.81 lbf.) and those required by the polymer treatment group (1.33 lbf.). Although force levels for the epoxy treatment group were lower than those of the uncoated control group (0.97 lbf.), the difference was not significant. There was a significant difference in force levels required by the polymer treatment group when compared to the uncoated control group and the epoxy treatment group.

0.019*0.025 NiTi

There was a significant difference ($p < 0.01$) between the force levels required by the uncoated control group (1.39 lbf.) and those of both the epoxy treatment group (1.05 lbf.) and the palladium treatment group (0.74 lbf.). There was a significant difference ($p < 0.01$) in force levels required when comparing the epoxy treatment group to both the uncoated control group (1.39 lbf.) and the polymer treatment group (1.46 lbf.). There was a significant difference ($p < 0.01$) between the force levels required by the palladium treatment group (0.74 lbf.) and the epoxy treatment group (1.05 lbf.), as well as between the polymer treatment group (1.46 lbf.) and the uncoated control group (1.39 lbf.).

0.019*0.025 SS

There was a significant difference ($p < 0.05$) in the force levels required by the polymer treatment group (1.30 lbf.) and the uncoated control group (0.97 lbf.). There were no other significant differences in this wire type and size.

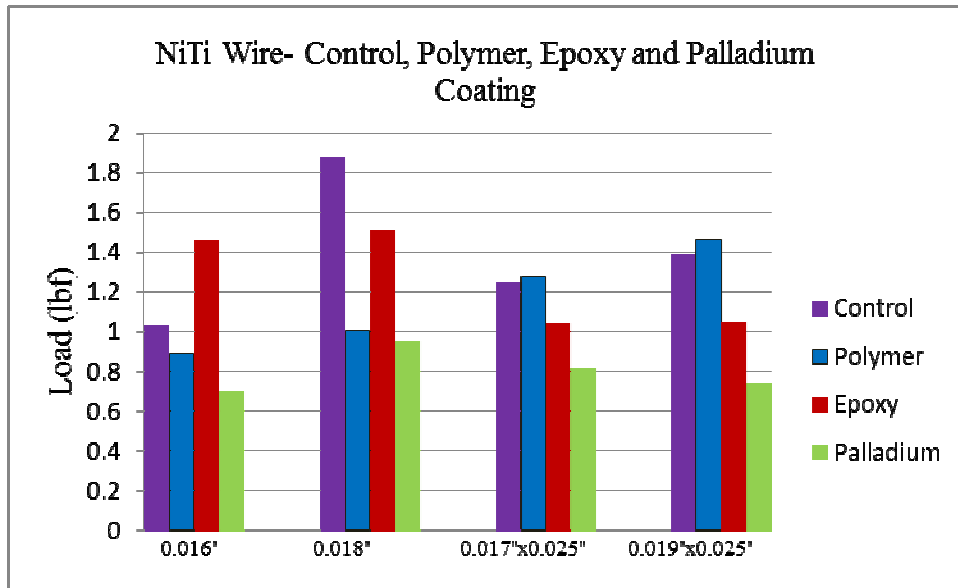


Figure 5 Mean force values for nickel-titanium wire sizes with no abrasion.

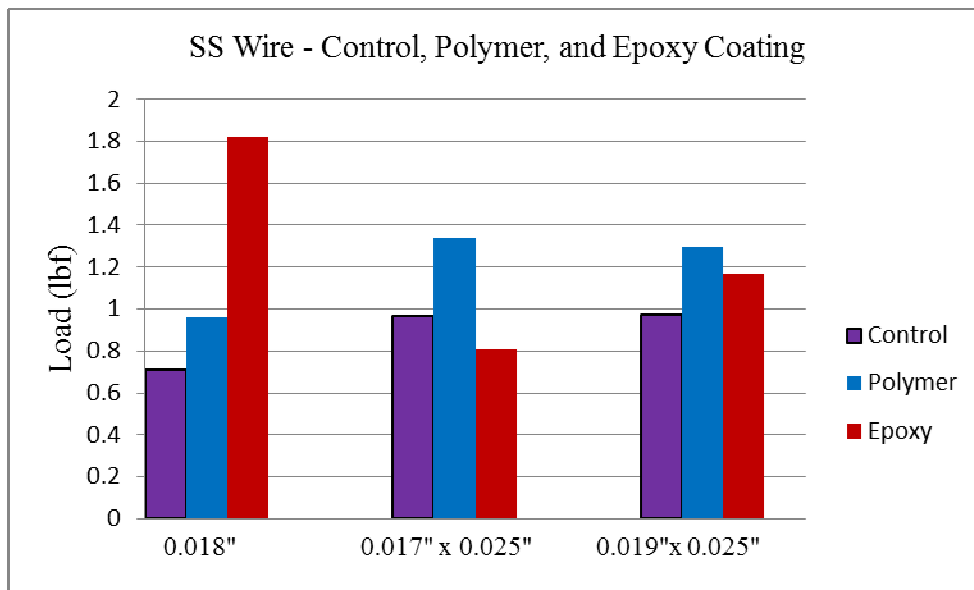


Figure 6 Mean force values for stainless steel wire sizes with no abrasion.

4.3 COATED UNABRADED COMPARED TO COATED AFTER ABRASION

0.016-in NiTi

Epoxy: After two minutes (0.79 lbf.), four minutes (1.25 lbf.) and eight minutes (1.09 lbf.) of abrasion (Figure 6) there was a statistically significant difference ($p < 0.05$) between this and its coated unabraded equivalent (1.46 lbf.). It should also be noted that the force level recorded at four minutes was greater than that recorded at both two and eight minutes.

Palladium: After two minutes (0.70 lbf.) and eight minutes (0.73 lbf.) there was no significant difference. At four minutes (1.00 lbf.), however, there was a significant difference ($p < 0.05$) when comparing it to the coated unabraded equivalent (0.70 lbf.).

Polymer: There were no significant differences at two minutes (0.69 lbf.), four minutes (0.76 lbf.) or eight minutes (0.83 lbf.) for this coating when comparing it to the coated unabraded equivalents (0.89 lbf.).

0.018-in NiTi

Epoxy: After two minutes (0.98 lbf.), four minutes (1.22 lbf.) and eight minutes (1.01 lbf.) of abrasion (Figure 7) there was a statistically significant difference ($p < 0.05$) for this wire in comparison to its coated unabraded equivalent (1.51 lbf.). It should also be noted that at four minutes the force level recorded was more than that recorded at both two and eight minutes.

Palladium: After two minutes of abrasion (1.23 lbf.) there was a significant difference ($p < 0.05$) when compared to its coated unabraded (0.95 lbf.). After four

minutes (1.13 lbf.) and eight minutes (1.04 lbf.) of abrasion there was no significant difference.

Polymer: After two minutes (0.79 lbf.) of abrasion there was a significant difference ($p < 0.05$) when compared to its coated unabraded equivalent (1.00 lbf.). After four minutes (0.93 lbf.) and eight minutes (0.91 lbf.) of abrasion there was no significant difference.

0.018-in SS

Epoxy: After two minutes (0.97 lbf.), four minutes (1.08 lbf.) and eight minutes (1.04 lbf.) of abrasion there was a statistically significant difference ($p < 0.05$) for this wire compared to its coated unabraded equivalent (1.82 lbf.).

Polymer: After two minutes (0.88 lbf.), four minutes (0.92 lbf.) and eight minutes (1.11 lbf.) of abrasion there was no significant difference ($p < 0.05$) when compared to its coated unabraded equivalent (0.96 lbf.).

0.017×0.025-in NiTi

Epoxy: After two minutes (1.02 lbf.), four minutes (0.86 lbf.) and eight minutes (1.10 lbf.) of abrasion (Figure 8) there was no significant difference ($p < 0.05$) when compared to its coated unabraded (1.04 lbf.) equivalent.

Palladium: After two minutes (1.22lbf.) and eight minutes (1.12 lbf.) of abrasion there was a significant difference ($p < 0.05$) when compared to its coated unabraded equivalent (0.82 lbf.). After four minutes (1.08 lbf.) of abrasion there was no significant difference in force levels required.

Polymer: After two minutes (1.06 lbf.), four minutes (0.96 lbf.) and eight minutes (0.94 lbf.) of abrasion there was a statistically significant difference ($p < 0.05$) for this wire in comparison to its coated unabraded (1.28 lbf.) equivalent.

0.017×0.025-in SS

Epoxy: After two minutes (1.07 lbf.) and eight minutes (1.02 lbf.) of abrasion there was a significant difference ($p < 0.05$) when compared to its coated unabraded equivalents (0.81 lbf.). After four minutes (0.9473 lbf) of abrasion there was no significant difference.

Polymer: After two minutes (1.30 lbf.), four minutes (1.12 lbf.) and eight minutes (1.18 lbf.) of abrasion there was no significant difference ($p < 0.05$) when compared to the coated unabraded (1.34 lbf.).

0.019×0.025-in NiTi

Epoxy: After two minutes (1.21 lbf.), four minutes (1.07 lbf.) and eight minutes (1.10 lbf.) of abrasion (Figure 9) there was no significant difference ($p < 0.05$) when compared to its coated unabraded equivalent (1.05 lbf.).

Palladium: After two minutes (1.07 lbf.) and four minutes (1.15 lbf.) of abrasion there was a significant difference ($p < 0.05$) when compared to its coated unabraded equivalent (0.74 lbf.). After eight minutes of abrasion (0.90 lbf.) there was no significant difference.

Polymer: After four minutes (1.06 lbf.) and eight minutes (0.76 lbf.) of abrasion there was a significant difference ($p < 0.05$) when compared to its coated unabraded

equivalent (1.46 lbf.). After two minutes (1.35 lbf.) of abrasion there was no significant difference.

0.019×0.025-in SS

Epoxy: After two minutes of abrasion (0.89 lbf.) there was a statistically significant difference ($p<0.05$) for this wire compared to its coated unabraded equivalent (1.17 lbf.). After four minutes (1.07 lbf.) and eight minutes (1.04 lbf.) of abrasion there was no significant difference.

Polymer: After two minutes (1.23 lbf.) and four minutes (1.14 lbf.) of abrasion there was no significant difference. After eight minutes of abrasion (1.07 lbf.) there was a statistically significant difference ($p<0.05$) for this wire compared to its coated unabraded wire equivalent (1.30 lbf.).

4.4 COMPARISON OF COATINGS AFTER ABRASION

0.016 NiTi

After two minutes of abrasion there were no statistically significant differences among the three treatment groups (Figures 10, 11, and 12). After four minutes of abrasion there was a significant difference ($p<0.01$) for the polymer treatment group (0.76 lbf.) when compared to both the epoxy treatment group (1.25 lbf.) and the palladium treatment group (1.00 lbf.). The force level required by the palladium treatment group (1.00 lbf.) was also significantly less when compared to the epoxy treatment group but significantly more when compared to the polymer treatment group. After eight minutes of abrasion

there was a significant difference ($p < 0.01$) for both the polymer treatment group (0.83 lbf.) and the palladium treatment group (0.73 lbf.) when compared to the epoxy treatment group (1.09 lbf.).

0.018 NiTi

After two minutes of abrasion there was a significant difference ($p < 0.01$) for both the polymer treatment group (0.79 lbf.) and the epoxy treatment group (0.98 lbf.) when compared to the palladium treatment group (1.23 lbf.). After four minutes of abrasion there was a significant difference ($p < 0.05$) for the polymer treatment group (0.93 lbf.) when compared to the epoxy treatment group (1.22 lbf.). The palladium treatment group was non-significant (1.13 lbf.). After eight minutes of abrasion there was no significant difference ($p < 0.05$) between the treatment groups as the average force levels were as follows: epoxy treatment group (1.01 lbf.), palladium treatment group (1.04 lbf.), and the polymer treatment group (0.91 lbf.).

0.018 SS

After two minutes of abrasion there was no significant difference ($p < 0.05$) between the epoxy treatment group (0.97 lbf.) and the polymer treatment group (0.88 lbf.). After four minutes of abrasion there was a significant difference ($p < 0.05$) for the polymer treatment group (0.92 lbf.) compared to the epoxy treatment group (1.08 lbf.). After eight minutes of abrasion there was no significant difference between the epoxy treatment group (1.04 lbf.) and the polymer treatment group (1.11 lbf.).

0.017×0.025-in NiTi

After two minutes of abrasion there was no significant difference ($p < 0.05$) between the groups, as the average force levels were as follows: the epoxy treatment group (1.02 lbf.), the palladium treatment group (1.22 lbf.), and the polymer treatment group (1.06 lbf.). After four minutes of abrasion there was a significant difference ($p < 0.05$) for the epoxy treatment group (0.86 lbf.) when compared to the palladium treatment group (1.08 lbf.). The polymer treatment group was not significant (0.96 lbf.). After eight minutes of abrasion there was no significant difference ($p < 0.05$) between the three groups. The average force levels were as follows: the epoxy treatment group (1.10 lbf.), the palladium treatment group (1.12 lbf.) and the polymer treatment group (0.94 lbf.).

0.017×0.025-in SS

After two minutes of abrasion there was a significant difference ($p < 0.05$) for the epoxy treatment group (1.08 lbf.) when compared to the polymer treatment group (1.30 lbf.). After four minutes of abrasion there was no significant difference ($p < 0.05$) between the epoxy treatment group (0.95 lbf.) and the polymer treatment group (1.12 lbf.). After eight minutes of abrasion there was no significant difference ($p < 0.05$) between the epoxy treatment group (1.02 lbf.) and the polymer treatment group (1.18 lbf.).

0.019×0.025-in NiTi

After two minutes of abrasion there was a significant difference ($p < 0.01$) between the polymer treatment group (0.76 lbf.) and both the epoxy treatment group (1.21 lbf.)

and the palladium treatment group (1.07 lbf.). After four minutes of abrasion there was no significant difference ($p < 0.05$) between the epoxy treatment group (1.07 lbf.), the palladium treatment group (1.15 lbf.) and the polymer treatment group (1.06 lbf.). After eight minutes of abrasion there was a significant difference ($p < 0.01$) for the polymer treatment group (0.76 lbf.) when compared to the epoxy treatment group (1.10 lbf.). The palladium treatment group (0.90 lbf.) was not significant.

0.019×0.025-in SS

After two minutes of abrasion there was a significant difference ($p < 0.01$) between the epoxy treatment group (0.88 lbf.) and the polymer treatment group (1.23 lbf.). After four minutes of abrasion there was no significant difference ($p < 0.05$) between the epoxy treatment group (1.07 lbf.) and the polymer treatment group (1.14 lbf.). After eight minutes of abrasion there was no significant difference ($p < 0.05$) between the epoxy treatment group (1.04 lbf.) and the polymer treatment group (1.08 lbf.).

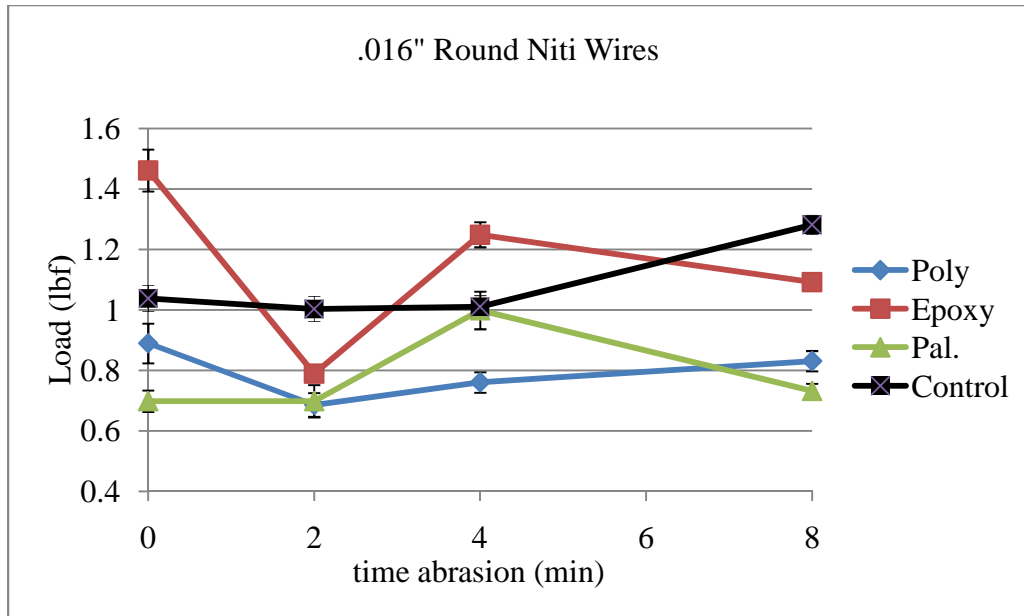


Figure 7 Mean force values for the three treatment groups at 0, 2, 4 and 8 minutes of abrasion (.016-in NiTi).

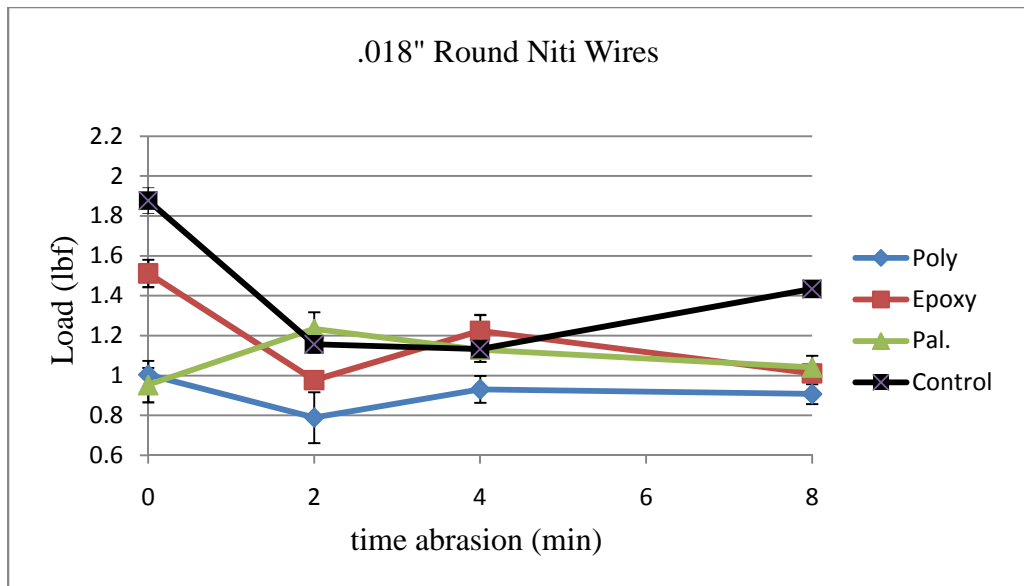


Figure 8 Mean force values for the three treatment groups at 0, 2, 4 and 8 minutes of abrasion (.018-in NiTi).

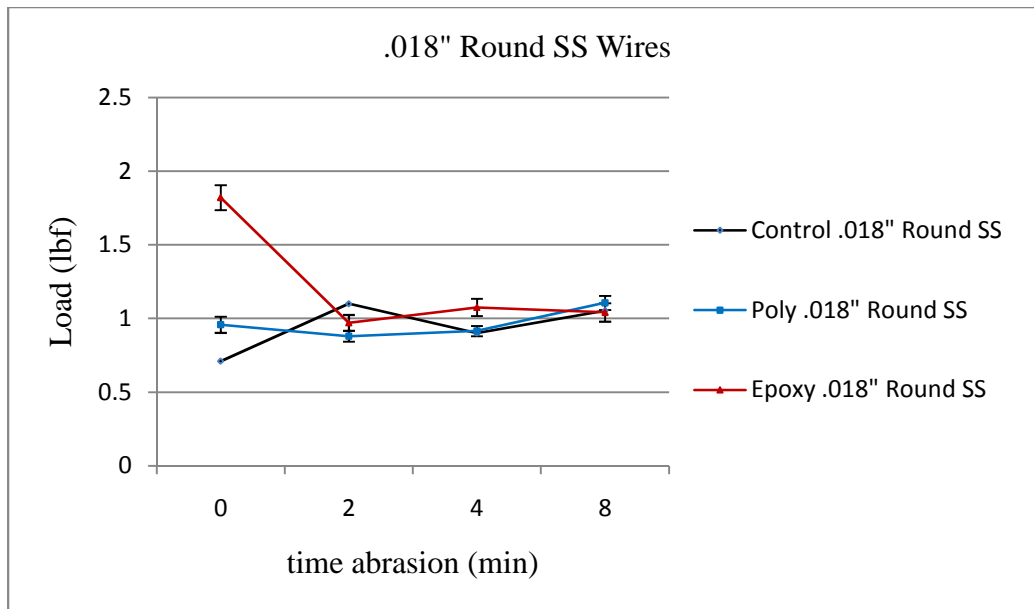


Figure 9 Mean force values for the two treatment groups at 0, 2, 4 and 8 minutes of abrasion (.018-in SS).

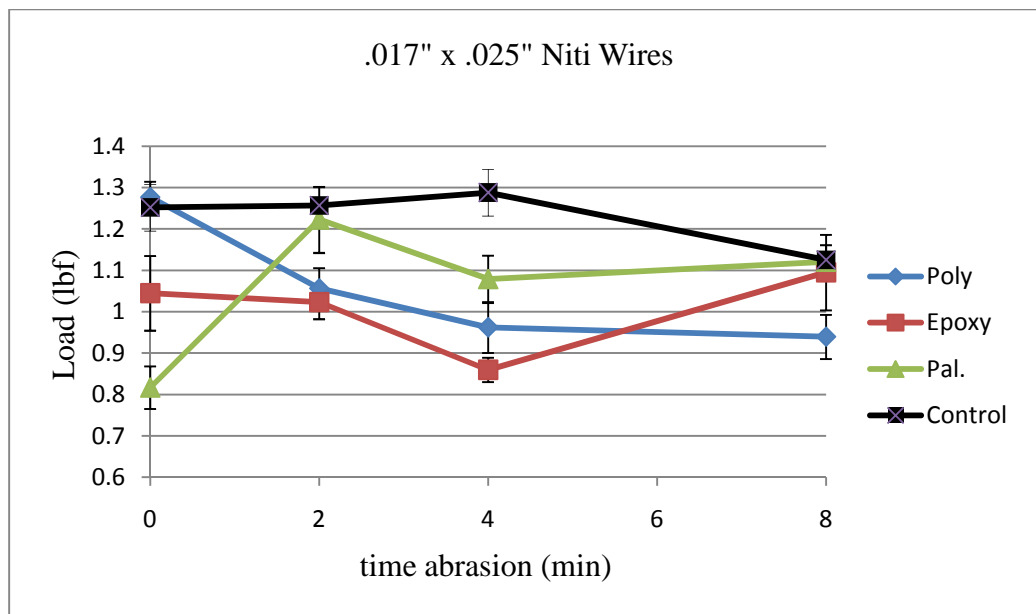


Figure 10 Mean force values for the three treatment groups at 0, 2, 4 and 8 minutes of abrasion (.017 x .025-in NiTi).

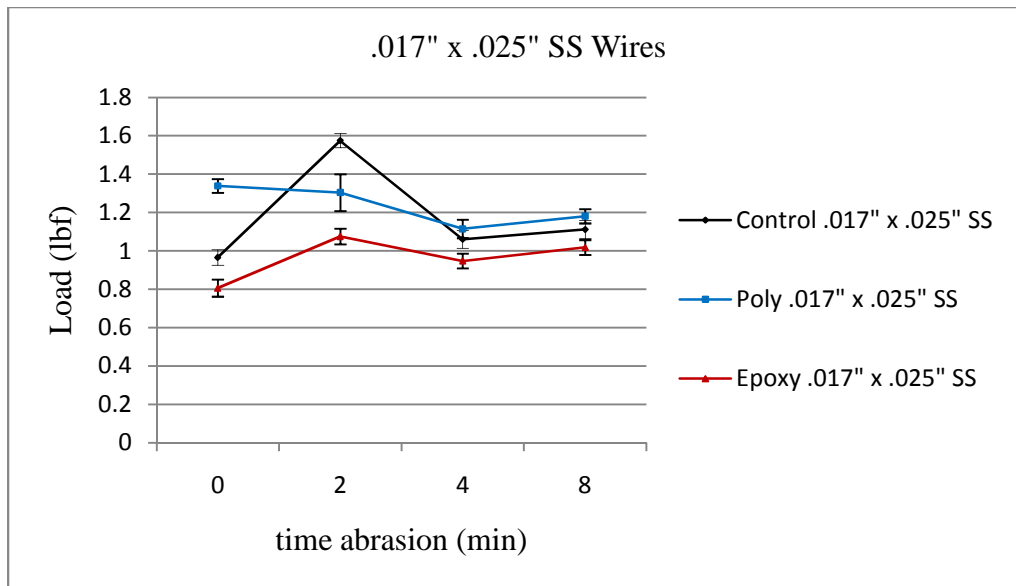


Figure 11 Mean force values for the two treatment groups at 0, 2, 4 and 8 minutes of abrasion ($.017 \times .025$ -in SS).

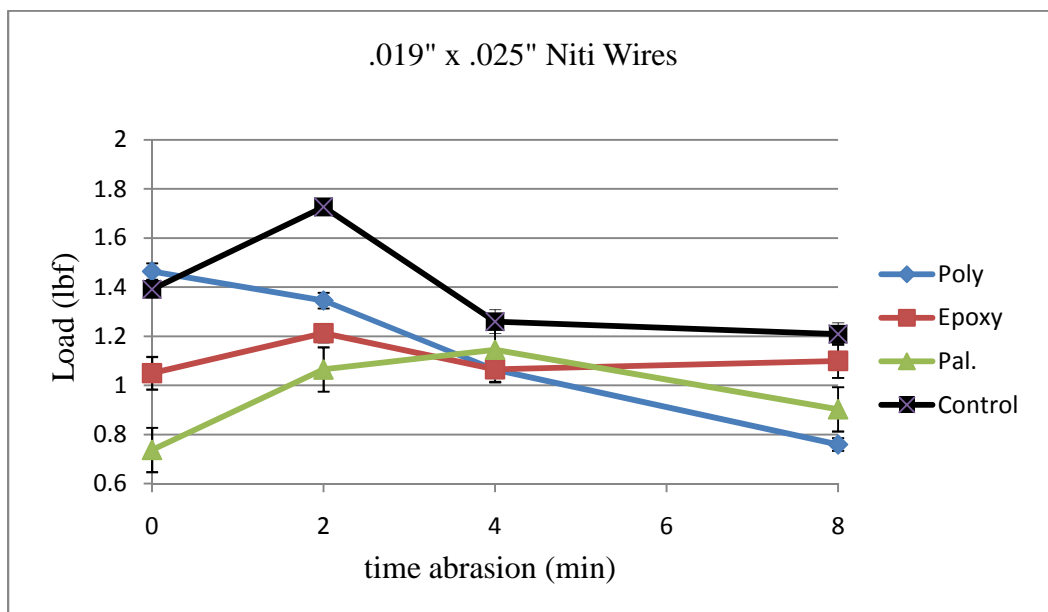


Figure 12 Mean force values for the three treatment groups at 0, 2, 4 and 8 minutes of abrasion ($.019 \times .025$ -in NiTi).

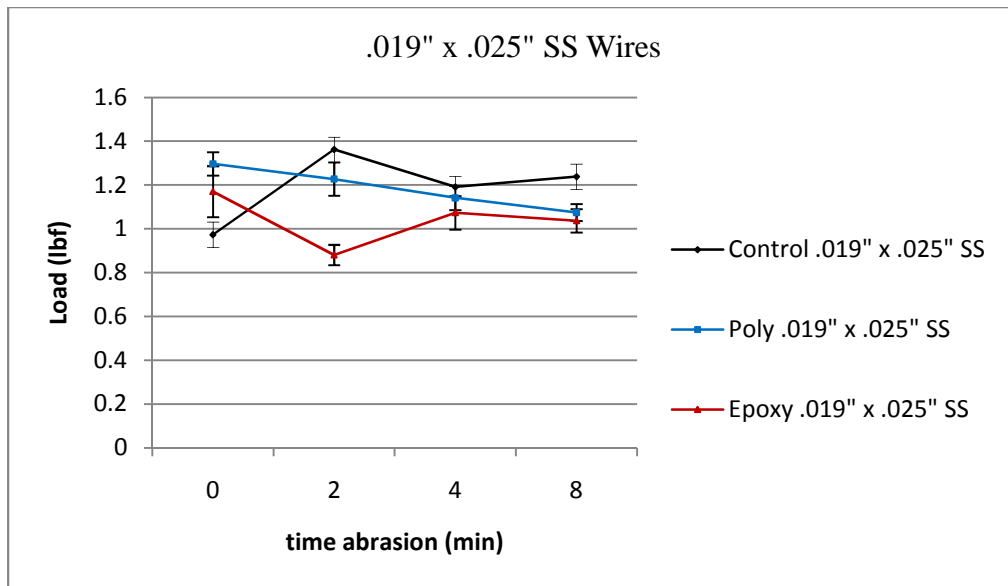


Figure 13 Mean force values for the two treatment groups at 0, 2, 4 and 8 minutes of abrasion (.019 × .025-in SS).

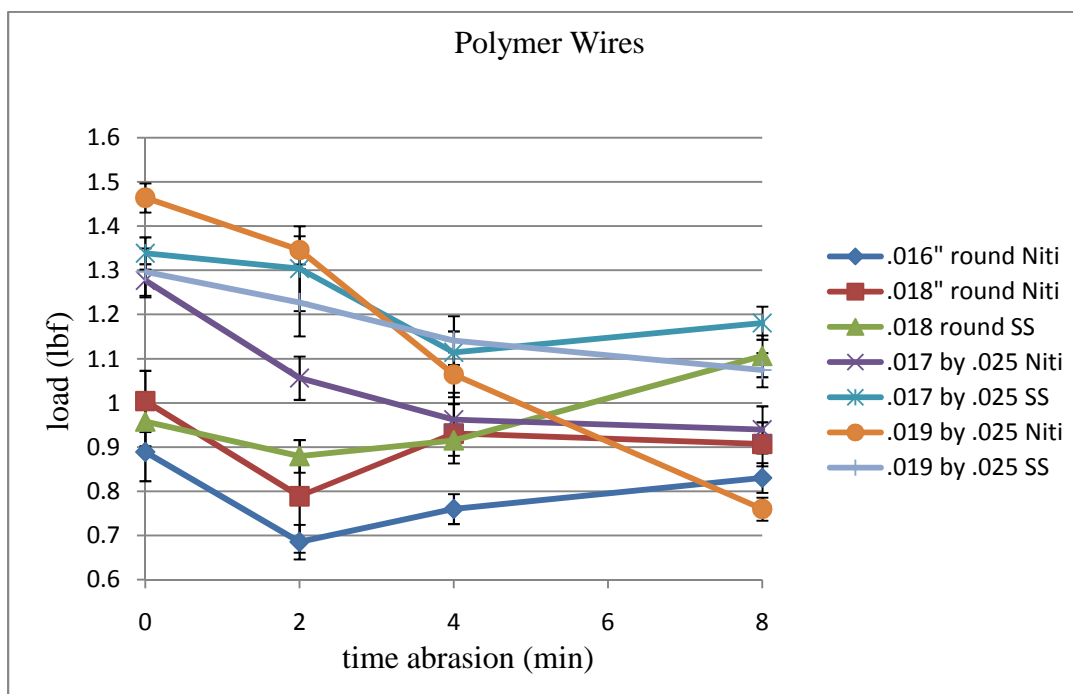


Figure 14 Mean force values for the polymer treatment group at 0, 2, 4 and 8 minutes of abrasion (All wire types and sizes tested).

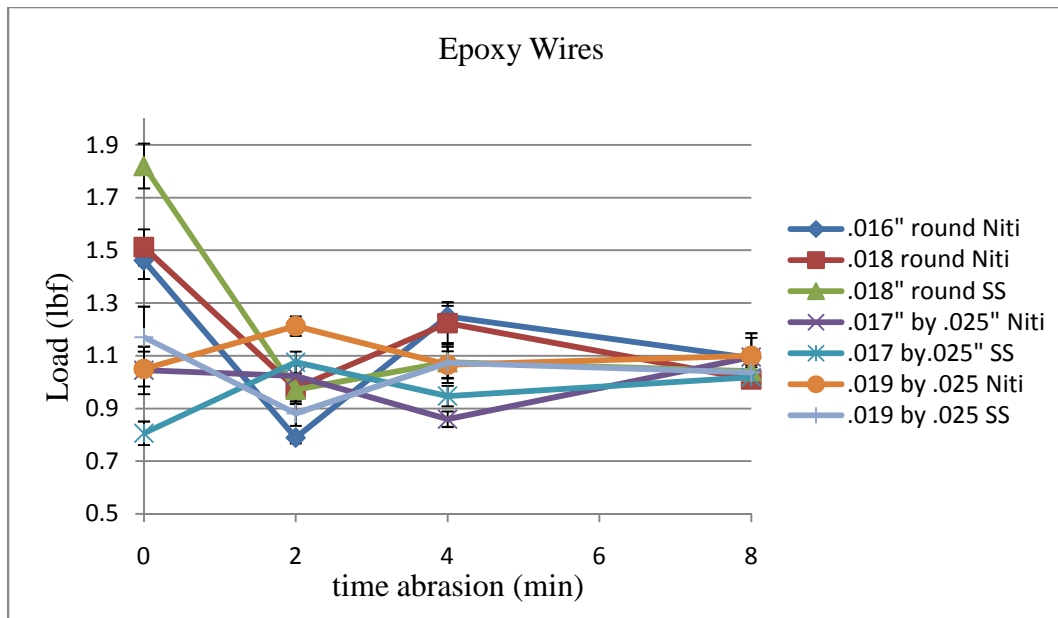


Figure 15 Mean force values for the epoxy treatment group at 0, 2, 4 and 8 minutes of abrasion (All wire types and sizes tested).

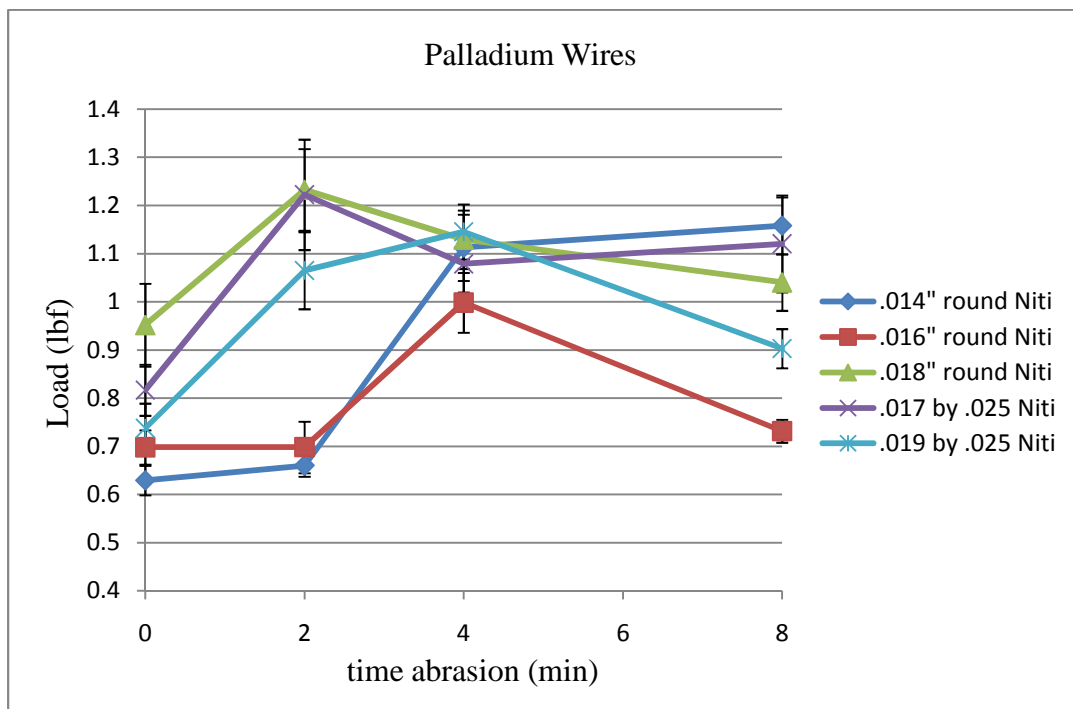


Figure 16 Mean force values for the palladium treatment group at 0, 2, 4 and 8 minutes of abrasion (All wire types and sizes tested).

Table 2

Mean Force Values and Standard Error of Control and Coated Wires

Coating	Wire Type and Size	0 min lbf.	SE	2 min. lbf.	SE	4 min. lbf.	SE	8 min. lbf.	SE
Non-Coated	.016" Round Niti	1.04	0.04	1	0.04	1.01	0.04	1.28	0.03
	.018" Round SS	0.71	0.04	1.09	0.04	0.91	0.04	1.05	0.05
	.018" Round Niti	1.88	0.06	1.16	0.04	1.13	0.07	1.43	0.04
	.017" x .025" Niti	1.25	0.06	1.26	0.04	1.29	0.06	1.13	0.03
	.017" x .025" SS	0.97	0.04	1.57	0.04	1.06	0.05	1.11	0.05
	.019" x .025" NiTi	1.39	0.03	1.73	0.04	1.26	0.05	1.21	0.05
	.019" x .025" SS	0.97	0.06	1.36	0.06	1.19	0.05	1.24	0.06
Polymer	.016" Round Niti	0.89	0.06	0.69	0.04	0.76	0.03	0.83	0.03
	.018" Round Niti	1.01	0.07	0.79	0.13	0.93	0.07	0.91	0.05
	.018" Round SS	0.96	0.06	0.88	0.04	0.92	0.04	1.11	0.05
	.017" x .025" Niti	1.28	0.04	1.06	0.05	0.96	0.06	0.94	0.05
	.017" x .025" SS	1.34	0.04	1.31	0.11	1.11	0.05	1.18	0.04
	.019" x .025" NiTi	1.46	0.03	1.35	0.03	1.07	0.05	0.76	0.03
	.019" x .025" SS	1.29	0.05	1.23	0.08	1.14	0.06	1.07	0.04
Epoxy	.016" Round Niti	1.46	0.07	0.79	0.02	1.25	0.04	1.09	0.03
	.018" Round Niti	1.51	0.07	0.98	0.04	1.22	0.08	1.01	0.03
	.018" Round SS	1.82	0.08	0.97	0.05	1.08	0.06	1.04	0.06
	.017" x .025" Niti	1.04	0.09	1.02	0.04	0.86	0.03	1.09	0.09
	.017" x .025" SS	0.81	0.05	1.07	0.04	0.95	0.04	1.02	0.04
	.019" x .025" NiTi	1.05	0.07	1.21	0.04	1.07	0.05	1.11	0.07
	.019" x .025" SS	1.17	0.11	0.88	0.05	1.07	0.08	1.04	0.05
Palladium	.016" Round Niti	0.69	0.04	0.69	0.05	0.99	0.06	0.73	0.02
	.018" Round Niti	0.95	0.09	1.23	0.08	1.13	0.06	1.04	0.06
	.017" x .025" Niti	0.82	0.05	1.22	0.11	1.08	0.06	1.12	0.11
	.019" x .025" NiTi	0.73	0.05	1.06	0.08	1.15	0.06	0.91	0.05

5.0 SUMMARY

The current social climate dictates a higher demand for an aesthetically pleasing smile. Providers must therefore be aware of the newest technological developments for an aesthetic orthodontic appliance system (fixed appliances and archwires). Providers should be cognizant of the availability of these new products as well as their advantages and disadvantages.

Most of the studies in the literature focus on frictional resistance with respect to either an epoxy coated or a polymer coated archwire. No study had yet evaluated and compared frictional resistance of both of these coatings with that of a palladium coating. The purpose of this study was to investigate the kinetic frictional resistance of three different treatment groups of archwires (epoxy coated, palladium coated and polymer coated) before and after toothbrush abrasion.

The force level required to pull a section of archwire through an experimental jig at a set rate of speed over a fixed distance was determined using a United testing device. The three treatment groups consisted of stainless steel and nickel titanium archwires with a tooth colored coating made from one of three different materials. The manufacturing process for each was different, but could not be reported in detail due to patent restrictions by the manufacturers.

5.1 COATED UNABRADED COMPARED TO UNCOATED

For the round NiTi wires (0.016-in and 0.018-in) all three treatment groups exhibited a reduction in frictional resistance when compared to their respective uncoated

control groups. This supports the results obtained by Farronato *et al.* 2011 where Teflon coated archwires were tested. The only exception was the epoxy coated 0.016-in wire, which exhibited an increase in frictional resistance. For the rectangular NiTi (0.017×0.019-in and 0.019×0.025-in) the epoxy treatment group and the palladium treatment groups exhibited a decrease in frictional resistance, while the polymer treatment group exhibited a slight increase (0.02 – 0.07lbf) in frictional resistance. For the SS wire sizes (0.018-in, 0.017-in × 0.025-in and 0.019-in × 0.025-in) all the epoxy treatment groups and polymer treatment groups exhibited an increase in frictional resistance with the exception of the epoxy coating on the 0.017×0.025-in wire, which showed a slight decrease (0.16 lbf.) in frictional resistance.

5.2 COATED UNABRADED COMPARED TO COATED AFTER ABRASION

The polymer treatment group exhibited a decrease in frictional resistance after two, four and eight minutes of abrasion for all wire types and sizes tested when compared to unabraded samples. The epoxy treatment group exhibited an increase in frictional resistance after two, four and eight minutes of abrasion for the following rectangular archwire types and sizes: 0.019×0.025-in NiTi and 0.017×0.025 SS. For all other wire types and sizes tested, the epoxy treatment groups exhibited a decrease in frictional resistance. The palladium treatment groups exhibited an increase in frictional resistance after two, four and eight minutes of abrasion for all rectangular and round archwire sizes tested (NiTi only).

5.3 DISCUSSION OF COATINGS AFTER ABRASION

Of the eighteen test groups, 16 groups consistently exhibited either an increase or decrease after two, four and eight minutes of abrasion. The two exceptions were the epoxy treatment group (0.017×0.025-in NiTi) and the polymer treatment group (0.018-in SS), where in each case after 8 minutes of abrasion there was an increase in frictional resistance as opposed to a decrease in frictional resistance that was recorded after two and four minutes of abrasion.

Within some of the individual sizes of archwire samples tested there are some minor increases or decreases after each session of abrasion. This may be attributed to manufacturing discrepancies, some coatings may be slightly rougher or smoother or there may be a difference in initial thickness. For example, within a group, if a particular sample started with a slightly rougher coating, then abrasion may have smoothed this archwire more than a sample that had a smoother coating and a reduced frictional resistance would be expected. A greater effect, increase or decrease depending on wire size and coating material, would also be expected if a particular coating was thicker or thinner. For some of the samples an initial roughness may be smoothed by the abrasion early but after 8 minutes there may be a microscopic depression created in the coating which could increase the frictional resistance by notching. By utilizing optical scanning microscopy, photographs were taken of the archwires with the biggest changes in frictional resistance before and after abrasion (Figures 16 and 17). No gross changes in the coatings were observed, therefore, manufacturing discrepancies could not be ruled out as a possible source for the slight increases and decreases observed after each abrasion cycle.

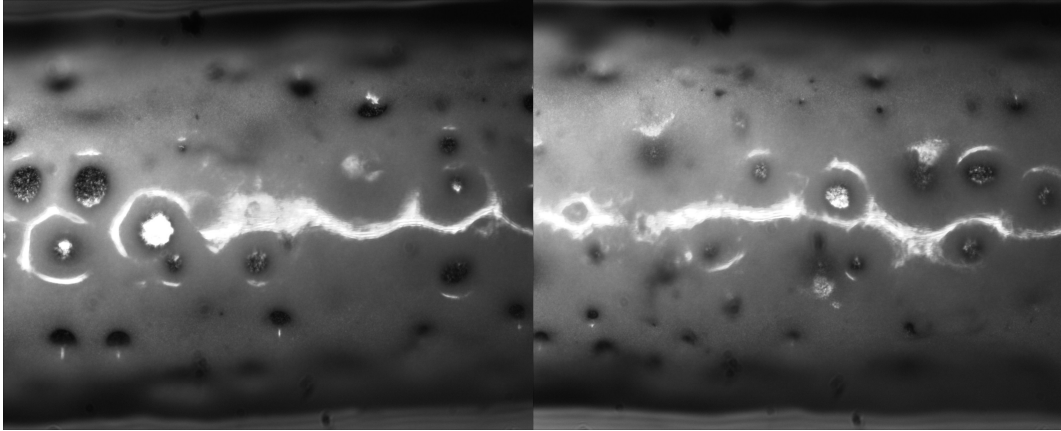


Figure 17 Unabraded (left) and abraded 8 minutes (right), 0.018-in SS Epoxy.

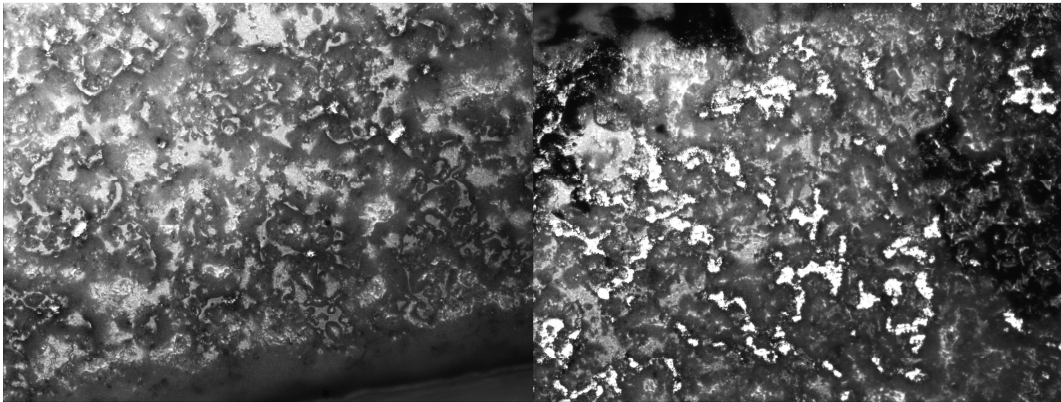


Figure 18 Unabraded (left) and abraded 8 minutes (right), 0.019x0.025-in NiTi Poly.

When comparing the results between treatment groups and control groups both with and without abrasion, there were many significant differences found that would indicate that the null hypothesis could be rejected. There was a statistically significant difference between the force levels required for the coated wires (including the epoxy coated, polymer coated, and palladium coated) when compared to the uncoated wires depending on the wire type. For the NiTi wires, there was a reduction in the force levels required for all three treatment groups. The palladium treatment group required a significantly lower force level than the uncoated equivalents in each size category. As

stainless steel samples of the palladium treatment group were not available, the results are only representative of NiTi wires with palladium coating. For the SS wires there was an increase in force levels for all three types of coatings, with the greatest discrepancy recorded between the 0.018 SS epoxy treatment group and its uncoated control group.

To aid in eliminating the possibility of increased frictional resistance due to the same brackets being used to test all archwire samples a baseline archwire size was run periodically throughout the experiment and there were no significant differences found at any test stage.

5.4 CLINICAL ADVANTAGES AND DISADVANTAGES OF COATED ARCHWIRES

For providers of orthodontic treatment the following conclusions can be drawn regarding the advantages and disadvantages of coated archwires from this experiment. Decreased frictional resistance for coated NiTi wires which can lead to quicker alignment times when using traditional ligation (elastics) and twin brackets. Increased frictional resistance for coated stainless steel wires is a major disadvantage when using sliding mechanics. The provider must take these findings into consideration when developing a treatment plan and the mechanics to be employed for alignment and space closure when using coated archwires.

5.5 CONCLUSIONS

- 1) Coated stainless steel archwires exhibited an increase in frictional resistance when compared to their uncoated equivalent archwires, while coated nickel-titanium archwires exhibited a decrease in frictional resistance when compared to their uncoated equivalent archwires.
- 2) After abrasion of the coated archwires there was an increase in frictional resistance for the palladium coated archwires compared to their coated non-abraded equivalents. In contrast, there was a decrease in frictional resistance for both the epoxy and polymer coated archwires after abrasion compared to their respective coated non-abraded equivalents.
- 3) The same effect on frictional resistance was displayed after two, four or eight minutes of abrasion for each coated archwire that was tested.

References

- Al-Khatib, S., Berradja, A., Celis, J. P., & Willems, G. (2005). In vitro friction of stainless steel arch wire-bracket combinations in air and different aqueous solutions. *Orthodontics & Craniofacial Research*, 8(2), 96-105. doi:10.1111/j.1601-6343.2005.00321.x
- Andreasen, G. F., & Quevedo, F. R. (1970). Evaluation of friction forces in the 0.022 × 0.028 edgewise bracket in vitro. *Journal of Biomechanics*, 3(2), 151-152, IN1-IN3, 153-160. doi:DOI: 10.1016/0021-9290(70)90002-3
- Angolkar, P. V., Kapila, S., Duncanson, M. G., Jr, & Nanda, R. S. (1990). Evaluation of friction between ceramic brackets and orthodontic wires of four alloys. *American Journal of Orthodontics and Dentofacial Orthopedics : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 98(6), 499-506.
- Baccetti, T., & Franchi, L. (2006). Friction produced by types of elastomeric ligatures in treatment mechanics with the preadjusted appliance. *The Angle Orthodontist*, 76(2), 211-216. Retrieved from <http://www.angle.org/doi/abs/10.1043/0003-3219%282006%29076%5B0211%3AFPBT0E%5D2.0.CO%3B2>
- Baker, K. L., Nieberg, L. G., Weimer, A. D., & Hanna, M. (1987). Frictional changes in force values caused by saliva substitution. *American Journal of Orthodontics and Dentofacial Orthopedics*, 91(4), 316-320. doi:DOI: 10.1016/0889-5406(87)90173-9

Berger, J. L. (1990). The influence of the SPEED bracket's self-ligating design on force levels in tooth movement: A comparative in vitro study. *American Journal of Orthodontics and Dentofacial Orthopedics*, 97(3), 219-228. doi:DOI: 10.1016/S0889-5406(05)80055-1

Burrow, S. J. (2009). Friction and resistance to sliding in orthodontics: A critical review. *American Journal of Orthodontics and Dentofacial Orthopedics : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 135(4), 442-447. doi:10.1016/j.ajodo.2008.09.023

Chimenti, C., Franchi, L., Di Giuseppe, M. G., & Lucci, M. (2005). Friction of orthodontic elastomeric ligatures with different dimensions. *The Angle Orthodontist*, 75(3), 421-425. doi:2

Clocheret, K., Willems, G., Carels, C., & Celis, J. P. (2004). Dynamic frictional behaviour of orthodontic archwires and brackets. *European Journal of Orthodontics*, 26(2), 163-170.

Doshi, U. H., & Bhad-Patil, W. A. (2011). Static frictional force and surface roughness of various bracket and wire combinations. *American Journal of Orthodontics and Dentofacial Orthopedics : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 139(1), 74-79. doi:10.1016/j.ajodo.2009.02.031

- Dowling, P. A., Jones, W. B., Lagerstrom, L., & Sandham, J. A. (1998). An investigation into the behavioural characteristics of orthodontic elastomeric modules. *British Journal of Orthodontics*, 25(3), 197-202.
- Drescher, D., Bourauel, C., & Schumacher, H. (1989). Frictional forces between bracket and arch wire. *American Journal of Orthodontics and Dentofacial Orthopedics*, 96(5), 397-404. doi:DOI: 10.1016/0889-5406(89)90324-7
- Ehsani, S., Mandich, M., El-Bialy, T., & Flores-Mir, C. (2009). Frictional resistance in self-ligating orthodontic brackets and conventionally ligated brackets. *The Angle Orthodontist*, 79(3), 592-601. Retrieved from <http://www.angle.org/doi/abs/10.2319/060208-288.1>
- Elayyan, F., Silikas, N., & Bearn, D. (2008). Ex vivo surface and mechanical properties of coated orthodontic archwires. *European Journal of Orthodontics*, 30(6), 661-667. doi:10.1093/ejo/cjn057
- Elayyan, F., Silikas, N., & Bearn, D. (2010). Mechanical properties of coated superelastic archwires in conventional and self-ligating orthodontic brackets. *American Journal of Orthodontics and Dentofacial Orthopedics : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 137(2), 213-217. doi:10.1016/j.ajodo.2008.01.026
- Farronato, G., Maijer, R., Caria, M. P., Esposito, L., Alberzoni, D., & Cacciato, G. (2011). The effect of teflon coating on the resistance to sliding of orthodontic archwires. *European Journal of Orthodontics*, doi:10.1093/ejo/cjr011

Fourie, Z., Ozcan, M., & Sandham, A. (2009). Effect of dental arch convexity and type of archwire on frictional forces. *American Journal of Orthodontics and Dentofacial Orthopedics : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 136(1), 14.e1-7; discussion 14-5. doi:10.1016/j.ajodo.2008.06.026

Fourie, Z., Özcan, M., & Sandham, A. (2009). Effect of dental arch convexity and type of archwire on frictional forces. *American Journal of Orthodontics and Dentofacial Orthopedics*, 136(1), 14.e1-14.e7. doi:DOI: 10.1016/j.ajodo.2008.06.026

Frank, C. A., & Nikolai, R. J. (1980). A comparative study of frictional resistances between orthodontic bracket and arch wire. *American Journal of Orthodontics*, 78(6), 593-609.

Goldberg, A. J., Burstone, C. J., Hadjinikolaou, I., & Jancar, J. (1994). Screening of matrices and fibers for reinforced thermoplastics intended for dental applications. *Journal of Biomedical Materials Research*, 28(2), 167-173.
doi:10.1002/jbm.820280205

Goldberg, A. J., Liebler, S. A., & Burstone, C. J. (2010). Viscoelastic properties of an aesthetic translucent orthodontic wire. *European Journal of Orthodontics*,
doi:10.1093/ejo/cjq150

Husmann, P., Bourauel, C., Wessinger, M., & Jager, A. (2002). The frictional behavior of coated guiding archwires. *Journal of Orofacial Orthopedics = Fortschritte Der*

*Kieferorthopadie : Organ/official Journal Deutsche Gesellschaft Fur
Kieferorthopadie*, 63(3), 199-211.

Ireland, A. J., Sherriff, M., & McDonald, F. (1991). Effect of bracket and wire composition on frictional forces. *European Journal of Orthodontics*, 13(4), 322-328.

Kapur Wadhwa, R., Kwon, H. K., Sciote, J. J., & Close, J. M. (2004). Frictional resistance in ceramic and metal brackets. *Journal of Clinical Orthodontics : JCO*, 38(1), 35-38.

Kapur, R., Sinha, P. K., & Nanda, R. S. (1999). Frictional resistance in orthodontic brackets with repeated use. *American Journal of Orthodontics and Dentofacial Orthopedics : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 116(4), 400-404.

Kusy, R. P. (1997). A review of contemporary archwires: Their properties and characteristics. *The Angle Orthodontist*, 67(3), 197-207. doi:2

Kusy, R. P. (2002). Orthodontic biomaterials: From the past to the present. *The Angle Orthodontist*, 72(6), 501-512. doi:2

Kusy, R. P., & Whitley, J. Q. (1997). Friction between different wire-bracket configurations and materials. *Seminars in Orthodontics*, 3(3), 166-177.

Lim, K. F., Lew, K. K., & Toh, S. L. (1994). Bending stiffness of two aesthetic orthodontic archwires: An in vitro comparative study. *Clinical Materials*, 16(2), 63-71.

Michelberger, D. J., Eadie, R. L., Faulkner, M. G., Glover, K. E., Prasad, N. G., & Major, P. W. (2000). The friction and wear patterns of orthodontic brackets and archwires in the dry state. *American Journal of Orthodontics and Dentofacial Orthopedics : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 118(6), 662-674.
doi:10.1067/mod.2000.105529

Neumann, P., Bourauel, C., & Jager, A. (2002). Corrosion and permanent fracture resistance of coated and conventional orthodontic wires. *Journal of Materials Science. Materials in Medicine*, 13(2), 141-147.

Neumann, P., Bourauel, C., & Jager, A. (2002). Corrosion and permanent fracture resistance of coated and conventional orthodontic wires. *Journal of Materials Science. Materials in Medicine*, 13(2), 141-147.

Neumann, P., Bourauel, C., & Jager, A. (2002). Corrosion and permanent fracture resistance of coated and conventional orthodontic wires. *Journal of Materials Science. Materials in Medicine*, 13(2), 141-147.

Nikolai, R. J. (1997). Orthodontic wire: A continuing evolution. *Seminars in Orthodontics*, 3(3), 157-165. doi:DOI: 10.1016/S1073-8746(97)80066-7

Peterson, L., Spencer, R., & Andreasen, G. (1982). A comparison of friction resistance for nitinol and stainless steel wire in edgewise brackets. *Quintessence International, Dental Digest*, 13(5), 563-571.

- Postlethwaite, K. M. (1992). Advances in fixed appliance design and use: 2. auxiliaries, adhesives, appliance care and debonding. *Dental Update*, 19(8), 331-335.
- Proffit, W. R. (2000). *Contemporary orthodontics. st louis: Mosby; 2000*
- Ramadan, A. A. (2003). Removing hepatitis C virus from polytetrafluoroethylene-coated orthodontic archwires and other dental instruments. *Eastern Mediterranean Health Journal = La Revue De Sante De La Mediterranee Orientale = Al-Majallah Al-Sihhiyah Li-Sharq Al-Mutawassit*, 9(3), 274-278.
- Russell, J. S. (2005). Aesthetic orthodontic brackets. *Journal of Orthodontics*, 32(2), 146-163. doi:10.1179/146531205225021024
- Stannard, J. G., Gau, J. M., & Hanna, M. A. (1986). Comparative friction of orthodontic wires under dry and wet conditions. *American Journal of Orthodontics*, 89(6), 485-491.
- Swartz, M. L. (2007). Fact or friction: The clinical relevance of in vitro steady-state friction studies. *Journal of Clinical Orthodontics : JCO*, 41(8), 427-32; quiz 439.
- Tidy, D. C. (1989). Frictional forces in fixed appliances. *American Journal of Orthodontics and Dentofacial Orthopedics : Official Publication of the American Association of Orthodontists, its Constituent Societies, and the American Board of Orthodontics*, 96(3), 249-254.
- Wichelhaus, A., Geserick, M., Hibst, R., & Sander, F. G. (2005). The effect of surface treatment and clinical use on friction in NiTi orthodontic wires. *Dental Materials :*

Official Publication of the Academy of Dental Materials, 21(10), 938-945.

doi:10.1016/j.dental.2004.11.011

Yao, Y., Fukazawa, K., Huang, N., & Ishihara, K. (2011). Effects of 3,4-dihydrophenyl groups in water-soluble phospholipid polymer on stable surface modification of titanium alloy. *Colloids and Surfaces.B, Biointerfaces*,

doi:10.1016/j.colsurfb.2011.06.034

Zufall, S. W., & Kusy, R. P. (2000). Sliding mechanics of coated composite wires and the development of an engineering model for binding. *The Angle Orthodontist*, 70(1), 34-47.

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