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An Investigation of the Friction, Wear and Corrosion Properties of Orthodontic Appliances.

by

Dr. David James Michelberger ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Orthodontics

Department of Oral Health Sciences

Edmonton, Alberta
Spring 1999

0-612-40088-3

University of Alberta

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Name of Author: Dr. David James Michelberger

Title of Thesis: An Investigation of the Friction, Wear and Corrosion Properties of Orthodontic Appliances.

Degree: Master of Science

Year this Degree Granted: 1999

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Quote Page

The distant mountains, that uprear
    Their solid bastions to the skies,
Are crossed by pathways, that appear
    As we to higher levels rise

Henry Wadsworth Longfellow

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled An Investigation of the Friction, Wear and Corrosion Properties of Orthodontic Appliances by David James Michelberger in partial fulfillment of the requirements for the degree of Master of Science in Orthodontics.

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Dedication

A special thank you to my dear wife, Julie, and my loving parents, Andreas and Maria for their support and encouragement.

Abstract

This study investigated the frictional resistance and wear patterns exhibited by titanium and stainless steel brackets used in conjunction with stainless and beta-titanium (TMA) archwires in the dry state and in the presence of human saliva.

In the dry state, stainless steel brackets tested with .016 inch flat stainless steel wire surfaces recorded the lowest coefficient of static friction mean (0.289), while titanium brackets paired with .016 inch flat TMA wire surfaces produced the highest mean (0.767). Stainless steel brackets had significantly lower coefficients of friction than titanium brackets for all wires except .020 inch round stainless steel wires ($p < 0.05$). TMA wires generally had significantly larger coefficients of friction than stainless steel wires. The increased friction of the titanium and TMA alloys is also reflected in the severity of their wear patterns. An inverse relationship between friction and archwire surface dimension was generally found for TMA wires. Round wires demonstrated lower coefficients of kinetic friction than the flat wire surfaces. Human saliva did not significantly affect friction except when titanium brackets were coupled with stainless steel wires. No evidence of stress corrosion was found when testing was performed with saliva.

Acknowledgement

I would first like to thank my supervisor, Dr. Paul Major, and my committee members Dr. Ken Glover, Dr. Reg Eadie, Dr. Gary Faulkner and Dr. Narasimha Prasad, for their advice and guidance throughout this endeavour.

I would also like to thank the orthodontic clinic instructors for their contributions to my knowledge of orthodontics and for making my orthodontic education a very fulfilling and enjoyable experience.

Thank you to my colleagues, Bob Kinniburgh, Phil Williamson and Mark Knoefel, for their friendship and all the memorable experiences during our orthodontic education.

I would also like to thank the orthodontic clinic staff for all their help, patience and assistance during my orthodontic education.

I would also like to thank the Canadian Foundation for the Advancement of Orthodontics and the McIntyre Fund, University of Alberta for their financial support in undertaking this research experiment.

Finally, thank you to Ormco Corp. and Dentaurum Inc. for kindly providing the orthodontic materials used in this experiment.

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List of Abbreviations and Symbols

A_r	real area of contact
BI	binding between orthodontic bracket and archwire
EDX	energy dispersive x-ray analysis
F	force of friction
FR	classical friction
k	wear coefficient
k_{abr}	abrasive wear coefficient
l	sliding distance
mm	millimeter(s)
μ	coefficient of friction
μ_d	coefficient of dynamic friction
μ_s	coefficient of static friction
μm	micron(s)
mV	millivolt(s)
N	normal force
nm	nanometer(s)
NO	notching
p	penetration hardness
RS	resistance to sliding
s	force required to shear a unit area of asperity contact
SEM	scanning electron microscope/microscopy

List of Abbreviations and Symbols (continued)

SS	stainless steel
Ti	titanium
TMA	beta-titanium wire (titanium-molybdenum alloy)
V	volume of material removed due to wear
w	wear rate

Chapter 1

Introduction and Literature Review

1.1 Introduction

Tooth movement using fixed orthodontic appliances is generally accomplished by three methods: closing loops in segmental archwires, closing loops in continuous archwires and sliding mechanics. The main factor which distinguishes sliding mechanics from closing loop mechanics is the production of frictional forces at the bracket-archwire interface as the bracketed tooth is moved along the wire with sliding mechanics. Consequently, the orthodontic forces applied must overcome these frictional forces in order to achieve tooth movement. Since orthodontic tooth movement is maximized by using light continuous forces, it would be beneficial to minimize the frictional force in order to enable the use of light forces and attain a more efficient orthodontic appliance.[1,2] The success of sliding mechanics, therefore, is dependent upon the tribological and frictional characteristics of this interface. These interfacial characteristics, in turn, are dependent on the archwire and bracket materials used. Archwires are available in four alloys (stainless steel, chrome-cobalt, nickel titanium and beta-titanium), two cross-sectional shapes (rectangular and round) and various sizes. Until recently, only two bracket compositions were available: stainless steel and ceramic. A few years ago, however, a new titanium bracket, Rematitan, was introduced by Dentaurum Inc. (Pforzheim, Germany). It has been suggested that this bracket may provide a method of favorably reducing the frictional resistance encountered with sliding mechanics and produce more efficient tooth movement.

1.2 Statement of the Problem

Research has established the detrimental effects of friction on orthodontic sliding mechanics. The orthodontic force aimed at accomplishing tooth movement must overcome the frictional resistance so that an adequate amount of force is experienced by the tooth and supporting structures in order to initiate the biological response required for tooth movement. Research has demonstrated that light continuous forces result in the most efficient tooth movement. Consequently, the smaller the frictional forces, the lighter the applied forces can be to achieve tooth movement. Since the frictional resistance is dependent on the material characteristics of the brackets and archwires, altering these properties may significantly influence orthodontic sliding mechanics. One such example is the introduction of titanium brackets by Dentaurum Inc. The increased biocompatibility and corrosion resistance of titanium, in addition to improved sliding mechanics are two characteristics which have been suggested as improvements over currently available orthodontic brackets.[3] Oxide layers on the surface of metals are protective in nature since they prevent metal to metal contact and thus reduce adhesion and friction. The thin and relatively impervious oxide layer of titanium may minimize adhesion, between these brackets and archwires, and result in reduced friction and enhanced sliding mechanics.[4] The oxide layer may also enhance the corrosion resistance of titanium brackets relative to stainless steel brackets in the presence of human saliva. Since the tribological properties of these brackets in conjunction with various orthodontic archwires have a direct impact on successful orthodontic treatment, it is imperative that the wear patterns and the friction coefficients of these brackets be researched.

Several investigators have studied the frictional coefficients of orthodontic brackets and archwires in the presence of artificial salivas to simulate the oral environment more closely. Recent research, however, demonstrated that the frictional coefficients for the same bracket-archwire combinations differed substantially between artificial salivas and human saliva. It was therefore concluded that artificial salivas did not provide a satisfactory substitute and only human saliva should be used to study the frictional resistance of orthodontic brackets and archwires in the wet state.[5] Therefore, tests were performed in the presence of human saliva as a means of simulating the oral environment.

1.3 Purpose

The objective of this study was to compare the coefficients of friction between various orthodontic archwire and bracket materials. Titanium and stainless steel orthodontic brackets were used in conjunction with .020 inch round and .016 X .022 inch rectangular stainless steel wires and .016 X .022 inch rectangular beta-titanium (TMA) archwires. This experiment compared the coefficients of friction of the different bracket and archwire alloys. The effects of archwire configuration and surface area were also investigated by comparing the coefficients of friction of .020 inch round stainless steel wires with the .016 inch and .022 inch flat surfaces of rectangular stainless steel wires. The .016 inch and .022 inch flat surfaces of the TMA archwires were also compared. Scanning electron microscopy (SEM) was utilized to analyze the wear patterns associated with several bracket and archwire combinations in order to determine the relationship between the frictional resistance and the wear pattern associated with the sliding process. Testing was undertaken in the dry state and in the presence of human saliva to simulate the oral environment more closely and assess the effect of saliva on frictional resistance. A "stick and slip" motion in the presence of human saliva was also studied to assess the influence of stress-corrosion on the frictional resistance at the bracket-archwire interface.

1.4 Research Questions

1. Is there a difference between the coefficient of static friction of titanium and stainless steel orthodontic brackets?
2. Is there a difference between the coefficient of kinetic friction of titanium and stainless steel orthodontic brackets?
3. Is there a difference between the coefficient of static friction of stainless steel and TMA archwires?
4. Is there a difference between the coefficient of kinetic friction of stainless steel and TMA archwires?
5. Is there a difference between the coefficient of static friction of stainless steel .020 inch round wire surfaces and .016 inch and .022 inch flat archwire surfaces?
6. Is there a difference between the coefficient of kinetic friction of stainless steel .020 inch round wire surfaces and .016 inch and .022 inch flat archwire surfaces?
7. Does a relationship exist between the bracket alloy and the wear pattern observed under the SEM?
8. Does a relationship exist between the archwire alloy and the wear pattern observed under the SEM?
9. Does a relationship exist between the archwire-bracket combination and the wear pattern observed under the SEM?
10. Is there a relationship between the coefficient of static friction and the wear pattern observed under the SEM?
11. Is there a relationship between the coefficient of kinetic friction and the wear pattern observed under the SEM?

12. Does the presence of human saliva at the archwire-bracket interface increase or decrease the coefficient of static friction compared to the dry state?

13. Does the presence of human saliva at the archwire-bracket interface increase or decrease the coefficient of kinetic friction compared to the dry state?

14. Does the coefficient of static friction increase with a "stick-slip" sliding motion in the presence of human saliva due to stress corrosion at the bracket-archwire interface?

15. Does the coefficient of kinetic friction increase with a "stick-slip" sliding motion in the presence of human saliva due to stress corrosion at the bracket-archwire interface?

1.5 Null Hypotheses

1. There is no significant difference between the coefficients of static friction of stainless steel and titanium brackets.
2. There is no significant difference between the coefficients of kinetic friction of stainless steel and titanium brackets.
3. There is no significant difference between the coefficients of static friction of stainless steel and TMA wires.
4. There is no significant difference between the coefficients of kinetic friction of stainless steel and TMA wires.
5. There is no significant difference between the coefficients of static friction of stainless steel .020 inch round wire surfaces and the .016 inch and .022 inch flat wire surfaces.
6. There is no significant difference between the coefficients of kinetic friction of stainless steel .020 inch round wire surfaces and the .016 inch and .022 inch flat wire surfaces.
7. Titanium and stainless steel brackets do not demonstrate different wear patterns as observed under the SEM.
8. TMA and stainless steel archwires do not demonstrate different wear patterns as observed under the SEM.
9. The various bracket-archwire combinations do not demonstrate different wear patterns as observed under the SEM.
10. The various wear patterns are not associated with significantly different levels of coefficients of static friction.

11. The various wear patterns are not associated with significantly different levels of coefficients of kinetic friction.

12. There is no significant difference between the coefficients of static friction in the dry and wet (human saliva) environments for the initial segment of a “stick-slip” sliding motion.

13. There is no significant difference between the coefficients of kinetic friction in the dry and wet (human saliva) environments for the initial segment of a “stick-slip” sliding motion.

14. There is no significant difference between the proportionate changes in the coefficients of static friction in the dry and wet (human saliva) environments for a “stick-slip” sliding motion.

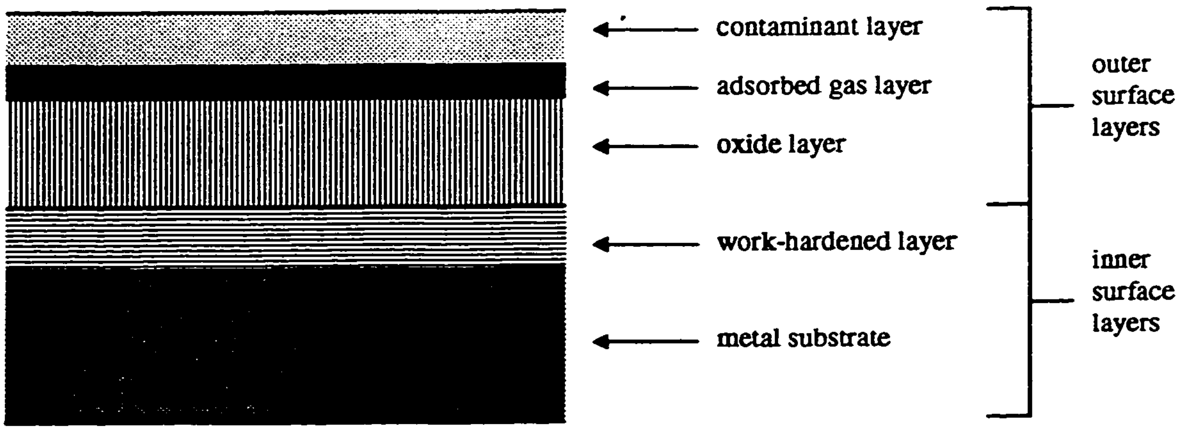
15. There is no significant difference between the proportionate changes in the coefficients of kinetic friction in the dry and wet (human saliva) environments for a “stick-slip” sliding motion.

1.6 An Overview of Tribology: Friction, Wear and Lubrication

Tribology is defined as the study of physics, chemistry, and engineering of interacting surfaces in relative motion. It consists of the elements of friction, wear, lubrication and adhesion. It is derived from the Greek word "tribos" which means rubbing.[6,7] Examining the tribological characteristics of a surface interface between two bodies entails both the investigation of the components of each of the individual surfaces as well as the interactions occurring between the two surfaces. The characteristics of an individual metal surface will be described first, followed by a description of the interactions occurring between two surfaces.

The surface of a metal substrate consists of two main layers, the outer surface and inner surface layers (Figure 1-1). The inner surface layer is further subdivided into a work-hardened layer and the metal substrate. The outer surface layer also consists of several layers. The outermost is the contaminant layer which is 5 nm thick and is often comprised of oil films. Below this is the adsorbed gas layer, which has a thickness of 0.5 nm, and mainly consists of molecules of water vapor and oxygen from the atmosphere. Beneath the adsorbed gas layer is the oxide layer which has a thickness of 10 nm. This layer results from the reaction between the oxygen from the air and the metal. Noble metals, such as gold, do not possess this layer.[8,9] The oxide layer is protective in nature and prevents adhesion. Thus, when the oxide layer is penetrated, the atoms of the adjacent surfaces come into close proximity and adhesion between the two surfaces is promoted.[7] The process of adhesion is described in more detail later.

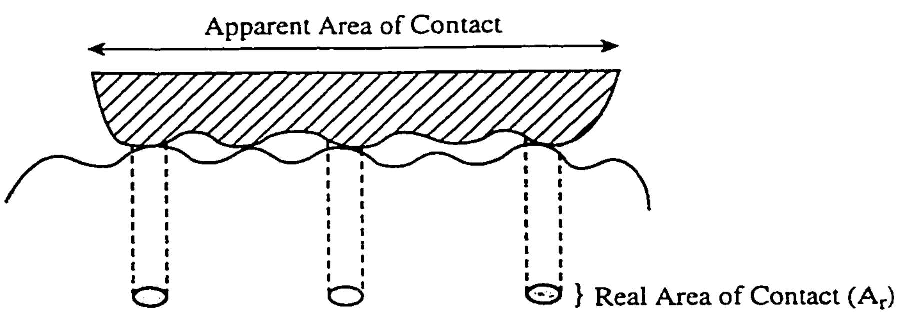
Figure 1-1. Composition of a Metal Surface



(modified from Czichos, 1978 and Rabinowicz, 1995)

When two surfaces are brought into contact, junctions between the microscopic peaks of the surfaces, called asperities, are formed and they are responsible for supporting the normal load and the frictional forces generated at the interface. The combination of all the asperity microcontact areas comprise the area of real contact between the surfaces. The apparent area of contact is the contact area assumed from a macroscopic prospective. It includes the real contact area and those areas which appear to be in contact but really are not (Figure 1-2).

Figure 1-2. A Schematic Representation of a Surface Interface



(modified from Rabinowicz, 1995)

The real area of contact, A_r, is much less than the apparent area of contact, and in the majority of cases is represented by the equation:

$$A_r = \frac{N}{p} \tag{1.1}$$

where N is the normal load applied and p is the penetration hardness. Penetration hardness represents the largest compressive stress a material can withstand without any plastic deformation. When two surfaces are brought into contact under a load, N, asperity deformation (plastic flow) occurs until the total contact area equals the value of N/p. Extremely smooth surfaces with very small asperities, however, may not demonstrate plastic deformation and only elastic deformation may occur leading to an area of real contact much larger than N/p.[9]

The physical properties of the two surfaces in contact influence the surface interactions between them. Two categories of parameters exist: the volume properties which relate the contacting bodies as a whole and the surface properties which determine the contact interface.[9] Volume properties include the elastic and plastic characteristics of a material such as hardness - a measure of a material's plastic strength. Surface properties include the chemical reactivity of the surfaces as governed by the outer surface layers and the inherent surface energy. The nature of the oxide layer has a tremendous impact on the chemical reactivity of a surface. A soft oxide layer, with a hardness not exceeding that of the metal tripled, tends to act as a lubricant. Hard, thin and brittle layers, on the other hand, are less effective since their integrity is more readily undermined and they break up.[9] The nature of the surface interactions represent important influences on the friction and wear characteristics of surface interfaces.

1.6.1 Friction

Friction is a phenomenon that has been investigated by scientists for several centuries and is defined as the resistance against the movement of two contacting bodies.[10] Although first described by Leonardo da Vinci in the middle of the fifteenth century, the first two laws of friction were rediscovered by Amontons approximately 200 years later. Coulomb is often credited with the third law. The laws of friction are as follows:[9,11]

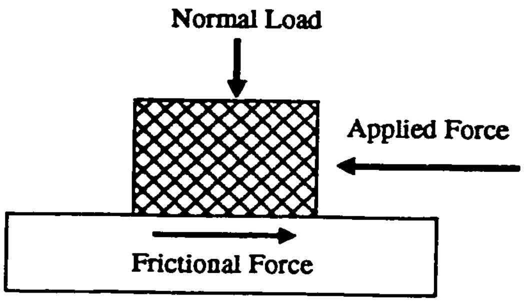
1. The frictional force is proportional to the normal load
2. The force of friction is independent of the apparent area of contact
3. The frictional force is independent of the sliding velocity

The first law of friction can be mathematically represented as,

$$F = \mu N \qquad (1\text{-}2)$$

where μ is the coefficient of friction, N is the normal load applied to the two bodies in contact and F is the frictional force at the interface between them. Thus, the coefficient of friction is the ratio between the frictional force and the applied normal load. The frictional force is always oriented parallel to the surfaces in contact and acts in the direction opposite to the applied force as shown in Figure 1-3.[9]

Figure 1-3. Frictional Force Between Two Surfaces



As mentioned previously, the interface between two surfaces is determined by the real contact area represented by the asperities in contact. If A_r represents the real contact area, and s represents the force required to shear a unit area of asperity contacts, the force of friction can be written as:

$$F = A_r s \tag{1-3}$$

Since the area of real contact is proportional to the normal load and independent of the size of the contacting bodies, it follows that friction is also independent of the size of the apparent area of contact. This explains the second law of friction.[6]

Exceptions to the laws of friction have been noted. One such example involves a soft substrate material covered by a thin, hard surface layer. At low loads, the hard surface layer remains intact and the frictional characteristics are governed by this hard layer. At higher loads, however, the surface layer is penetrated and the properties of the substrate now predominate. Thus, in this situation, the first law of friction is not obeyed. Although friction is generally considered to be independent of surface roughness, this is not completely true. For example, the friction associated with very smooth surfaces and very rough surfaces can be quite large. In the first scenario, a large frictional force results since the real area of contact is quite large. In the second situation, the friction is large since the asperities of one surface must be lifted over the asperities of the other. The intermediate range of surface roughnesses, however, do display the independence of friction from surface roughness.[9]

There are two types of friction - static friction and kinetic or dynamic friction. Static friction represents the resistance to initial motion, while kinetic friction is the force required to maintain motion. Common observation has demonstrated that the static frictional force is greater than the dynamic frictional force. Thus, the same relationship exists for the coefficients of static friction (μ_s) and dynamic friction (μ_d). Three mechanisms have been proposed to explain the larger value for static friction. Firstly, when two objects are in static contact, the junctional contact areas increase as a result of creep and these must be sheared to initiate movement. Secondly, as the duration of this static contact increases, stronger atomic interactions at the asperity junctions result from increased atomic diffusion across the interface. Finally, penetration of surface films may also be a factor. In a static situation, an applied tangential force, albeit less than the force of friction, may initiate the degradation of the surface film between the two bodies prior to movement, leading to a larger static frictional force. Translatory movement, on the other hand, results in less effective breakdown of the surface layer, and thus the dynamic friction is less than the static friction.[6]

1.6.2 The Process of Sliding Friction

The process of sliding friction consists of two components: the adhesion force developed at asperity contacts and the deformation force needed to plow the harder surface asperities through those of the softer surface.[7,11] Adhesion is defined as the attractive or tensile force across an interface between two surfaces.[7,10,11] Van der Waals forces, metallic forces, ionic bonds and covalent bonds represent the various bonding mechanisms of adhesion.[8] Adhesion occurs when oxide and contaminant-free metallic surfaces are brought into contact. For example, pressing a steel rod into a freshly-scraped surface of indium results in fragments of indium adhering to the end of the rod when the rod is detached. While the adhesive forces are atomic in nature, the deformation forces are mechanical in nature.[6,7,11]

It has been generally observed that the process of sliding one material over another at slow speeds results in intermittent oscillations rather than a smooth, continuous movement. This phenomenon is termed "stick-slip sliding". Motion of a body is achieved when the applied force overcomes the static frictional force. Sliding ensues since the force of kinetic friction is usually less than that of static friction. This movement continues as long as the force of kinetic friction is exceeded. Once the kinetic friction overcomes the applied force, however, movement stops and "sticking" occurs. The cycle is then repeated when the static frictional force is overcome.[6]

The phenomenon of sliding friction can be divided into three distinct stages: establishment of asperity microcontacts between the surfaces, physiochemical modifications of the asperity junctions and finally, the rupturing of the microcontacts.[7] Two types of microcontacts between opposing surfaces exist: the mechanical interference between opposing asperities and the penetration of the asperities from the harder substance into the softer material (Figure 1-4). Most of the microcontacts result from both processes occurring simultaneously.

Figure 1-4. Two Types of Asperity Contacts

a) mechanical interference b) penetration

(modified from Glaeser, 1993)

The continuation of movement between surfaces, once initiated, is attributed to the physiochemical changes which occur within the microcontacts. These changes can be categorized as reversible or irreversible, stabilized or progressive and shallow or deep. Reversible changes disappear with their cause, while irreversible changes remain even with the removal of the cause. Stabilized changes are those which cease to progress in the continued presence of their cause. Shallow changes are located within the outermost surface layers while deep changes are those occurring in the subsurface layers.

Failure or rupturing of the asperity contact is the final step and it occurs in three forms: failure without any change in the geometry of the contacting asperities, failure involving geometrical change of the asperities and failure associated with material transfer from one asperity to another. The type of failure observed is governed by the geometry of the contacting asperities, the magnitude of the interference or depth of penetration and the mechanical properties of the materials at the moment of failure. Contact failure whereby the original shape of the asperities is maintained is referred to as elastic deformation. For this to occur, the shear strength of the adhesive bonds between asperities must be less than the cohesive strength of the materials involved. Plastic deformation describes contact failure whereby the shape of the asperities is changed by the sliding process. Interacting asperities are flattened and the deformed material is pushed aside as the harder material grooves the softer surface in a process known as plowing. In order for the transfer of material to occur at the interface, the shear strength of the adhesive junction must be stronger than the cohesive force of the weaker material.[7] Thus, when two different metals slide across one another and the oxide layers are penetrated, particles of the softer material are transferred onto the surface of the harder material in a process called adhesive wear.

The severity and nature of the frictional process can also be categorized as either mild or severe.[9] Severe friction results in prominent wear tracks attributed to the harder material plowing through the softer surface. Large transfer particles, with a diameter measuring larger than 50 μm, may be visible. A graphic output often reveals large irregular, fluctuations in the frictional force levels. Mild friction, on the other hand, results in fine lines or striations. Furthermore, any transfer particles observed are smaller (with a diameter of less than 25 μm) than those observed during a severe frictional process.

1.6.3 Wear

Wear is defined as the loss of material associated with geometrical changes due to moving, contacting bodies.[10] Two "macroscopic rules" of wear in dry, sliding environments have been experimentally observed:[8]

1. The wear rate, w, (the volume of material, V, removed per unit sliding, l) is proportional to the normal load, N:

$$w = \frac{V}{l} \propto N \tag{1-4}$$

2. The wear rate, w, is independent of the apparent area of contact, but can be related to the real area of contact.

Four mechanisms of wear exist: adhesive, abrasive, surface fatigue wear and tribo-chemical wear or corrosive wear. They may occur alone or in concert in a given tribological system. The various forms of wear are distinguished by studying the appearance of the surfaces involved (Table 1-1).

Table 1-1 Surface Appearances Associated with the Various Forms of Wear

Wear Mechanism	Surface Appearance
Adhesion	cones, flakes, pits, particles
Abrasion	scratches, grooves, striations
Surface fatigue	cracks, pits
Corrosive	reaction products (films, particles)

(modified from Czichos, 1978)

1.6.3.a Surface Fatigue Wear

Surface fatigue wear results from repeated stress cycling of the surfaces without requiring direct physical contact between them. This is the classic mode of failure observed in bearing systems, even when the surfaces are fully separated by a lubricant. Material failure is indicated by surface cracks and pits resulting from the fluctuating stresses of repeated wear.[8]

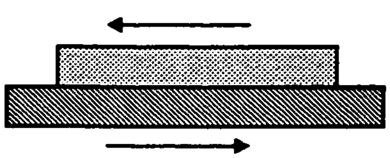
1.6.3.b Corrosive Wear

Corrosive wear, also termed tribochemical wear, is associated with the continual formation and removal of reaction products as a result of a dynamic interaction between the surfaces and a corrosive environment.[8,9] This wear process has been subdivided into two stages. The first stage involves the formation of reaction products on the surfaces of the contacting bodies due to their interactions with the environment. Subsequent removal of this film during the sliding process represents the second stage. This leads to the exposure of "fresh" unreacted surfaces which react with the environment and initiate another cycle. The interaction of the contact surfaces with the environment distinguishes corrosive wear from the other forms of wear.[8]

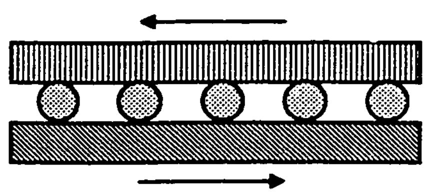
1.6.3.c Abrasive Wear

Abrasive wear occurs when the asperities from a harder surface plow through a softer countersurface.[6,8,9] Several categories of abrasive wear have been described. Firstly, abrasive wear can be subdivided as either two-body or three-body abrasion depending on the number materials in the system as illustrated in Figure 1-5. Furthermore, abrasive wear can be classified as gouging abrasion, grinding abrasion or erosion abrasion.

Figure 1-5. Two-Body and Three-Body Abrasion



a) Two-Body Abrasion



b) Three-Body Abrasion

It has been demonstrated that the abraded wear volume of a metal, V, is linearly associated with the normal load, N, and the sliding distance, l, and inversely proportional to the hardness of the softer material, p. The abrasive wear coefficient is represented by k_{abr}:[8,9]

$$V = \frac{k_{abr} N l}{p} \tag{1-5}$$

1.6.3.d Adhesive Wear

Adhesive wear involves the rupturing of asperities and subsequent transfer of fragments to the countersurface as a result of the interfacial adhesive forces being stronger than the asperity mechanical strength.[6,8,9] It is generally found that particles from the softer surface are transferred to the harder surface because of the weaker internal forces within the softer material relative to the atomic interactions across the interface. It has also been demonstrated, however, that fragments of the harder material may be transferred to the softer surface. This arises when an asperity junction coincides with a region of decreased strength within the harder material.[9] Three laws of adhesive wear have been devised as a result of extensive research in this field:[9]

1. The amount of wear is directly proportional to the applied load, N.
2. The amount of wear is proportional to the sliding distance, l.
3. The amount of wear is inversely proportional to the hardness of the surface, p, being worn away.

Thus, the volume of adhesive wear can be expressed as:

$$V = \frac{k N l}{3p} \tag{1-6}$$

where k represents the wear coefficient (the probability that a junction leads to the formation of a transferred particle).

A positive correlation between friction and adhesive wear has been found and it has been attributed to the fact that similar factors affect both phenomenon. Generally, the adhesive wear coefficient of metals increases as the fourth power of the coefficient of friction.[9]

The extent of wear observed may be categorized as either mild or severe, whereby the size of debris and wear rates are distinguishing factors. Mild wear is characterized by debris with particle sizes from 0.01 μm to 1 μm, while severe wear is characterized by the production of larger particles ranging from 20 μm to 200 μm.[8,11] The debris associated with mild wear is predominantly oxide and the surface is relatively smooth since the majority of the interface consists of oxide contact with occasional direct metallic contact. Severe wear, on the other hand, results in metallic debris and an increase in surface roughness as the oxide layer is penetrated and direct metallic contact predominates. As mentioned previously, the oxide layer is protective in nature and decreases adhesion between metals. Upon its penetration, fresh metal is exposed and adhesion is possible. Oxidation of the exposed surface from the atmosphere, however, competes with the cold welding to the adjacent metallic surface. The transition between mild and severe wear is thus dependent on the equilibrium between two competing processes: exposure of the metallic surface and oxidation of that surface by the surrounding atmosphere.[11]

Various mechanisms of sliding wear of metals have been proposed. While plastic deformation represents a common process, the mechanism of asperity fragmentation distinguishes them. The first mechanism attributes wear to the plastic flow at an asperity tip followed by particle detachment. As the asperity from the stronger surface contacts an asperity from the opposing softer surface, successive layers from the soft asperity shear off and particle growth occurs. Eventually, complete crack propagation within the weaker asperity ensues and this multi-layer wear particle is transferred to the harder surface since the interfacial adhesive contact is greater than the cohesive strength of the weaker material.[12]

While the aforementioned mechanism outlines the growth of wear debris prior to its actual deposition, another mechanism relates wear to the immediate adhesive transfer of wear debris to the adjacent surface with particle growth occurring afterwards. The particle produced from the rupturing of the weaker asperity immediately adheres to the countersurface and essentially becomes a new asperity on that surface. Continued sliding leads to subsequent fragments adhering to the original particle to form a larger aggregate particle which eventually detaches.[13] This particle may become flattened to a plate-like structure as it is compressed between the two surfaces.

1.6.4 Lubrication

The previous sections clearly indicate that surface interactions between two contacting solids can be very dynamic and complex. In order to reduce these phenomena, lubricants may be introduced between these surfaces. Thus, a lubricant is defined as a substance placed between surfaces in relative motion in order to alter the interactions occurring at the interface.[9,11] Lubricants are generally used to reduce the frictional force, the amount of wear and surface adhesion between two surfaces. Successful outcomes require a lubricant with a shear strength less than the solids between which it is interposed. Even if a lubricant does not completely prevent asperity contact between the two surfaces, it may reduce friction slightly by reducing the number and strength of asperity junctions.[11]

There are two main types of lubrication: solid lubrication and fluid lubrication. Fluid lubrication can be further subdivided into hydrostatic lubrication, hydrodynamic lubrication, elastohydrodynamic lubrication and boundary lubrication.

1.6.4.a Solid Film Lubrication

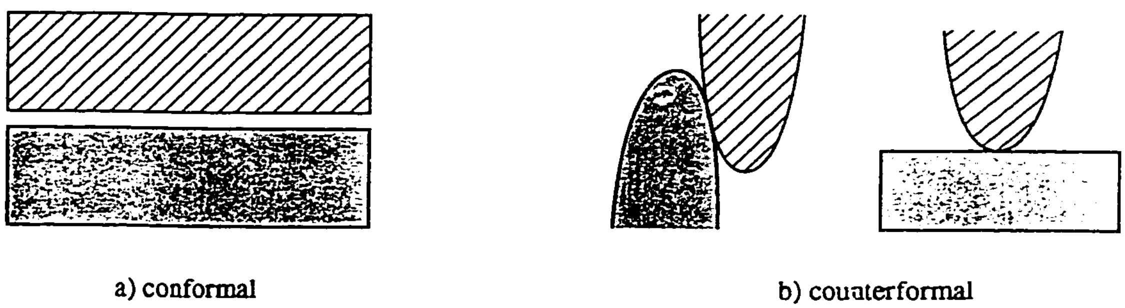
Solid lubrication involves the presence of a solid layer between the sliding surfaces. This layer can arise from two mechanisms: it may be applied to the surfaces (electroplating), or it may be formed by the reaction between the sliding surface and the environment (oxide layer formation). The mechanical characteristics of the solid layer determine its influence on the friction recorded between the two surfaces in motion. If the solid layer is brittle and easily broken up, shearing will occur in the weaker substrate during the sliding process since the lubricant layer is no longer intact. Similarly, if the solid lubricant film is stronger than the shear strength of the bulk of the weaker sliding material, the same outcome occurs. Consequently, the solid lubricant does not change the frictional properties of the interface in the above situations. It is therefore clear that for a solid layer to act as a lubricant, it must have a shear strength less than that of one of the sliding materials so that shearing will take place within the solid lubricant or at one of the solid layer - substrate junctions. This leads to a reduction in friction relative to the unlubricated environment.

1.6.4.b Fluid Lubrication

Fluid lubrication involves the presence of a liquid or gas film between two moving surfaces.[9,11] Hydrodynamic lubrication involves the presence of a relatively thick fluid film which separates two conformal surfaces (Figure 1-7). This entails two surfaces which are separated by a small gap and are closely matched in dimensions. The normal load applied to the two surfaces is supported by the viscous forces in the lubricant, which arise from the relative motion of the two surfaces.[11]

Elastohydrodynamic lubrication entails a lubricated interface involving counterformal surfaces as shown in Figure 1-7. The non-conforming surfaces result in very small contact regions which produce pressures much larger than those encountered in hydrodynamic lubrication and elastic distortion of the surfaces occurs. The lubricant film is very thin and the thickness generally varies from a few tenths of a micrometer to a few micrometers.

Figure 1-7. Distinguishing Conformal and Counterformal Geometries



(modified from Hutchings, 1992)

Boundary lubrication generally consists of surfaces separated by a thin lubricating layer comprised of an adsorbed molecular film. The thin nature of this film makes it vulnerable to penetration and therefore appreciable asperity contact occurs.[8,9,11] Therefore, the bulk rheological properties of the lubricant become less important than in hydrodynamic lubrication due to the presence of asperity contacts.[8] These conditions are often present under high contact pressures and low sliding speeds.[11] The lubricants involved with boundary lubrication are generally hydrocarbons, such as oils and carboxylic acids, and their interaction with the surfaces is either by physical adsorption, chemical adsorption or chemical reaction. Physical adsorption consists of weak van der Waals forces between the lubricant and surface in addition to lateral cohesive forces between adjacent hydrocarbon chains. Chemical adsorption is distinguished from physical adsorption by the presence of chemical bonds between the lubricant molecules and the surface. The most stable boundary lubricant film is produced when a chemical reaction between the solid surface and the lubricant produces a new compound at the interface.[8]

Temperature, sliding speed and load also have an impact on lubrication. The surface temperature is the most influential parameter and three different lubricant phases are distinguished with an increase in temperature: the solid phase, the liquid phase and the desorbed stage. With the advancement into each stage, there is a concomitant increase in friction. Within each phase, however, the friction remains relatively unchanged. Each transition is accompanied with a sudden increase in friction and the transition temperature between the solid and liquid stage often corresponds closely with melting temperature of the lubricant.[9]

It has been previously outlined that friction is independent of speed. Although this is true for minor variations, very large increases may influence friction particularly in lubricated situations. Increasing the speed may induce frictional heating which may cause the lubricant to reach a transition temperature, resulting in increased friction and wear.[9]

As stated earlier, the coefficient of friction is independent of load. However, high loads may lead to the deterioration of the lubricant and result in fusion of asperity junctions across an interface. Furthermore, increasing the load may raise the temperature of the system and induce a phase transition of the lubricant, increasing the friction as described previously.[9]

1.7 Frictional Resistance in Orthodontic Appliances

The frictional resistance encountered during sliding mechanics has been well established in the orthodontic literature and it consists of complex interactions between the bracket, archwire and method of ligation. Tooth movement associated with sliding mechanics has been described as a series of short steps involving oscillating tooth tipping and uprighting, rather than a smooth, continuous gliding-like process.[14,15,16] Both static and kinetic friction are present at the bracket-archwire interface during orthodontic tooth movement. Upon initial appliance activation, the force applied to the bracket must overcome the static friction between the bracket and archwire in order to accomplish the desired tooth movement. As the tooth translates, kinetic friction is present as the tooth rotates in the occlusal plane and tips in the sagittal plane. The rotation and tipping observed are a consequence of the moments created since the applied force is occlusal and buccal to the center of resistance. Tooth tipping temporarily ceases when the binding angle has been achieved and the binding friction is greater than the applied force. This occurs when the archwire contacts both the mesial and distal slot edges of the bracket. The archwire may also bend to accommodate the angulated bracket resulting in reaction forces between these two components.[17] A couple between the archwire and the bracket arises and uprights the tooth alongside periodontal remodelling. This "friction lock" is then overcome as the tooth uprights and the applied force overcomes the frictional resistance at the bracket-archwire interface. Another cycle is then initiated.

Several researchers have studied and analyzed the static and kinetic frictional forces encountered between various archwires and brackets. Downing *et al.* (1994) found that the static frictional force was always greater than the kinetic frictional force, while other researchers recorded kinetic frictional forces which fluctuated above and below the level of static friction.[18-24] These increased.kinetic frictional forces were attributed to variations in the archwire dimensions along its length, which affected the interacting experimental components and consequently the normal force at the bracket-archwire interface.[22]

The overall resistance to sliding in orthodontic appliances was described as a combination of several phenomena:[25]

$$RS = FR + BI + NO \tag{1-7}$$

where RS represented the resistance to sliding, FR represented the classical friction, BI represented binding between the bracket and archwire and NO represented the phenomenon of archwire notching. The classical friction comprised of the adhesion and plowing of asperities as described previously. At a minimal bracket-archwire angulation and torque, friction was mainly due to FR. In an active configuration, where a large bracket-archwire angulation was introduced, binding and notching became much more prominent.

Orthodontic practitioners have been aware of the importance of the above interactions and thus considerable research has been performed in this area. This has led to technological advances aimed at decreasing the friction between orthodontic brackets, archwires and method of ligation, thereby resulting in more efficient tooth movement. As the friction at the bracket-archwire interface increases, the efficiency of the orthodontic system diminishes. In other words, the proportion of the applied force that is actually transmitted into tooth movement decreases as the friction increases.[25] Many confounding factors of friction encountered with orthodontic biomechanics have been established and their influences have been assessed. A list of variables which can have an impact on friction is outlined in Table 1-2.

Table 1-2. Factors Influencing Friction in Orthodontic Appliances

1. Bracket-Archwire Orientation and Interactions
    a) second order angulation (tip) between the archwire and bracket
    b) third order angulation (torque) between the archwire and bracket
    c) relative level of adjacent brackets
    d) surface interactions and wear

2. Bracket Characteristics
    a) composition
    b) width
    c) surface roughness
    d) slot size and interbracket distance
    e) surface hardness

3. Archwire Characteristics
    a) composition
    b) cross-sectional shape and size
    c) surface roughness
    d) hardness
    e) stiffness

4. Ligation Force and Method

5. The Point of Application of the Retraction Force

6. Intraoral Variables
    a) fluid media
    b) forces associated with oral functions
    c) biological resistance

1.7.1 Bracket-Archwire Orientation and Interactions

1.7.1.a Second order angulation (tip) between the archwire and bracket

It was found that with non-binding second order angulations, the amount of tip had a minimal influence on friction, while bracket width and ligature force were the primary factors. When binding angulations were attained, however, the amount of tip became the primary influence on friction.[16] It was shown that friction generally increased with the second order angulation between the bracket and archwire in an almost linear relationship.[16,19,26-31] Exceptions did exist, however, with sapphire brackets (A Company, Inc, San Diego, U.S.A.).[32] Stainless steel archwires had the greatest increase in friction with an increase in the bracket-archwire angulation compared to nickel-titanium and coaxial stainless steel wires.[27]

1.7.1.b Third order angulation (torque) between archwire and bracket

Increasing the torque also increased frictional resistance, but not as dramatically as tip. On average, increasing torque by one degree resulted in frictional force increases of 0.11 N to 0.15 N.[31]

1.7.1.c Relative level of adjacent brackets

The presence of a vertical discrepancy between adjacent brackets resulted in increased frictional resistance.[33,34] These findings demonstrated the clinical importance of leveling and aligning prior to using sliding mechanics for space closure.

1.7.1.d Surface Interactions and Wear

An oxide layer is formed on the surface of most metals when they are exposed to oxygen. Chromium oxide and chromium hydroxide form on the surface of stainless steel while a thin and relatively impervious oxide film forms on the surface of titanium.[4,25,35] These films are protective in nature and they minimize adhesion between contacting metals. When they are penetrated or disrupted, however, adhesion between the two metal surfaces may occur. This phenomenon was observed when beta-titanium archwires were tested with stainless steel brackets.[22] Scanning electron microscopy and x-ray elemental analyses revealed that debris from beta-titanium archwires adhered to stainless steel surfaces due to galling and cold welding.[22,23] TMA deposits were found on ceramic brackets as well, but they were a result of abrasive wear rather than adhesive wear.[20] These interactions were considered the primary cause for the higher frictional forces associated with beta-titanium archwires.[22]

1.7.2 Bracket Characteristics

1.7.2.a Composition

The two main categories of brackets are metal brackets and esthetic brackets. Metal brackets are currently manufactured from stainless steel, chromium-cobalt and titanium. Stainless steel brackets are usually produced from type 300 stainless steels and can be further distinguished as either sintered or cast according to their manufacturing process.[25,33,36] The esthetic brackets can be subdivided into alumina ceramic brackets, zirconium oxide (zirconia) ceramic brackets and ceramic-reinforced composite brackets. The alumina brackets are further distinguished by their crystalline structure as either polycrystalline or monocrystalline as well as by their manufacturing process as either sintered or injection molded. Some of the composite and ceramic brackets also have metal slots.

The majority of studies reported that stainless steel brackets had decreased friction compared to ceramic brackets.[14,19,28,32,37-42] Some investigators attributed this to the increased roughness of ceramic brackets, while others attributed it to the chemical structure of ceramic brackets.[14,32,41,43,44] A few researchers, however, produced different results.[18,38,45] Ceramic-reinforced composite brackets produced less friction than stainless steel brackets and ceramic-reinforced composite brackets with metal slots when the .018 inch slot size was investigated. When .022 inch slot brackets were tested, however, ceramic-reinforced brackets with metal slots and stainless steel brackets were associated with the least friction.[45] Another study found no significant difference between stainless steel and polycrystalline ceramic brackets.[18] With respect to esthetic brackets, composite brackets demonstrated less friction than ceramic brackets, and single crystal alumina brackets tended to have less friction than polycrystalline alumina brackets.[19,32] Zirconium oxide brackets were found to have variable friction relative to polycrystalline alumina brackets.[44,46] Although the above studies indicated that different brackets had different frictional resistances, some researchers found that bracket material did not influence friction as much as archwire material.[18,22]

The manufacturing process and bracket design may also influence the frictional characteristics of orthodontic brackets. Recent investigations found that sintered stainless steel brackets reduced friction by as much as 40 to 45% relative to cast stainless steel brackets.[33,36] This was attributed to the sintering process resulting in smooth, rounded corners, whereas cast brackets had sharper edges resulting from the milling or cutting process.[33] Injection molded ceramic brackets appeared to be smoother than sintered ceramic brackets and this may have accounted for the decreased friction of injection molded brackets.[40]

1.7.2.b Bracket Width

The effect of bracket width has received considerable attention and various observations were noted. Several investigators reported that friction generally increased with bracket width in the presence or absence of bracket-archwire second order angulations.[16,29,47,48] In some experiments, however, this may have been due to the use of elastic ligatures whereby they would be stretched less with narrower brackets and thus result in a decreased ligature force relative to the wider brackets.[48] Increased friction with wider brackets has been attributed to the fact that binding would occur sooner due to a decreased binding angle relative to narrower brackets.[29]

In contrast to the above observations, some researchers demonstrated that narrower brackets produced more friction than wider brackets when a counterbalancing force (representing biologic forces) was applied against the retraction force.[15,40,49] This mechanical advantage of the wider brackets, however, diminished as the counterbalancing load was increased.[40] It was suggested that the wider brackets had less friction as a result of the smaller binding angle, relative to narrower brackets, which resulted in decreased bracket-wire contact forces.[1,40] Another study demonstrated that the effect of bracket width on frictional resistance should be evaluated in conjunction with the point of application of the retraction force.[50] When the force was applied at the level of the bracket slot, the narrow brackets produced significantly more friction than the wide brackets. When the force was applied gingival to the bracket slot, however, opposite results were recorded. In contrast to the many studies reporting contradictory findings regarding the relationship of bracket width and frictional resistance, some researchers found that bracket width did not have a significant effect on the frictional resistance of orthodontic brackets.[26,30]

Recognizing that empirical and statistical methods of assessing friction produced contrasting results regarding the effect of bracket width on frictional resistance, Schlegel, (1996) devised a planar mechanical model which mathematically described the influence of bracket width.[17] This analysis revealed that neither of the bracket width extremes were correct. The optimal bracket width was a function of the length of archwire along which the bracketed tooth was to be translated and its position along this length. Friction was the least when the translating bracket was in the center of the archwire span. Calculations revealed that a wider bracket would produce less friction at the center of the archwire span while a narrower bracket would produce less friction when the bracket was not centrally located.

1.7.2.c Surface Roughness

Several investigators analyzed and compared the surface roughness of different orthodontic brackets using scanning electron microscopy. There was overall agreement that stainless steel brackets had smoother and less porous surfaces than ceramic brackets and that monocrystalline ceramic brackets had smoother surfaces than their polycrystalline counterparts.[18,20,28,38,41] The influence of surface roughness on friction, however, appeared variable since not all investigators found a positive correlation between surface roughness and frictional resistance. For example, a few investigators reported that ceramic brackets had decreased friction relative to stainless steel brackets and that monocrystalline brackets had frictional levels similar to polycrystalline ceramic brackets.[18,20,38,45] Another study attributed the increased friction of ceramic brackets to their surface roughness since the ceramic brackets produced more archwire damage than stainless steel brackets during sliding mechanics.[41]

1.7.2.d Slot Size and Interbracket Distance

It was generally found that the bracket slot size had a minimal influence on friction.[22,49] It is important to recognize, however, that the archwire size utilized must also be considered. For example, it was observed that an .018 X .025 inch stainless steel archwire produced more friction in an .018 inch slot than in an .022 inch slot, whereas an .016 X .022 inch stainless steel archwire in an .018 inch slot produced less friction than either of the above combinations.[49] The influence of interbracket distance on frictional resistance was also investigated and it was concluded to be insignificant.[16]

1.7.3 Archwire Characteristics

1.7.3.a Composition

Archwire composition was a significant factor in determining the level of friction in an orthodontic appliance.[22] Beta-titanium and nickel titanium archwires generally produced more friction than stainless steel and chromium-cobalt archwires.[15,20-23,28,36-38,42,45,46,48,49,51] Nickel titanium wires produced twice the friction of stainless steel wires and beta-titanium produced a fivefold increase in friction over stainless steel wires.[49] Multistranded rectangular stainless steel archwires also produced less friction than rectangular nickel titanium and beta-titanium archwires regardless of the bracket-archwire angulation.[28] Chrome-cobalt had a frictional resistance similar to nickel titanium, but significantly less than beta-titanium when a pentamorphic arch form was used.[51] An esthetic polyacetyl wire was also investigated and it was determined to be unacceptable for orthodontic purposes since it underwent considerable plastic deformation during the experimental process.[38] The second order bracket-archwire angulation also influenced the frictional characteristics of various archwire materials. At low angulations stainless steel and chrome-cobalt wires produced less friction than nickel titanium wires. At angulations of 5-10 degrees or higher, however, nickel titanium wires recorded the least friction. This was attributed to the lower modulus of elasticity of nickel titanium wires which resulted in decreased contact forces and moments across the bracket-archwire interface relative to stainless steel and chrome-cobalt wires.[16,19,30,32]

1.7.3.b Archwire Cross-Sectional Dimension and Shape

Frictional resistance generally increased with an increase in archwire dimension.[14-26,18,26,28,30,33,36,37,38,44,48,49,52-55] Not all sequential increases in archwire size, however, were significant. For example, negligible differences were observed between .017 X .025 inch, .018 X .025 inch and .019 X .025 inch stainless steel wires, but they all produced significantly more friction than .016 X .022 inch wires.[54] Exceptions to the relationship between archwire size and level of friction were noted. Among the nickel titanium wires, the largest rectangular wires displayed the least frictional resistance.[36] Similarly, stainless steel archwires demonstrated an inverse relationship between size and friction in ceramic brackets.[14] This may have been attributed to the increased bracket and archwire contact with light wires secondary to the distortion of these lighter wires in the bracket slot as larger bracket-archwire angulations were introduced.[14] Furthermore, larger and stiffer wires had a decreased binding angle since they filled the slot more and this may have decreased friction.[56]

Although it was found that rectangular archwires generally produced more friction than round wires, exceptions were noted.[16,19,26,30,33,36,37,42,53,55,56] The importance of considering the occlusogingival dimension of the wires when assessing the influence of archwire geometry was also established. For example, 0.016 inch and .016 X 0.022 inch stainless steel wires used in conjunction with 0.0185 inch slot brackets had similar frictional levels.[15] Furthermore, .020 inch round archwires produced more friction at binding angulations than rectangular archwires with smaller occlusogingival dimensions.[16,30] These findings may have several rationales. Firstly, larger wires were stiffer and the normal component of force between the wire and bracket increased with archwire stiffness when binding occurred.[1,16] Secondly, the increased pressure associated with the point contact of round wires with the bracket edge as opposed to a line contact produced with rectangular archwires may have resulted in these findings.[16] The influence of archwire geometry and dimension on the frictional force was more pronounced at large bracket-archwire angulations.[16,19] It appears that both size and shape in conjunction with archwire-bracket angulation are important considerations in assessing frictional resistance of orthodontic appliances.

1.7.3.c Surface Roughness

Surface roughness of orthodontic archwires has been investigated with the SEM, profilometry and specular reflectance (laser spectroscopy). Surface analysis revealed that stainless steel had the smoothest surface, followed by chromium cobalt, TMA and nickel titanium respectively.[22,23,52,57] It was generally reported that friction did not always increase with an increase in surface roughness.[22,23,51,57] For example, although TMA demonstrated a smoother surface than nickel titanium, it had a greater coefficient of friction.[22,23] Furthermore, nickel titanium wires from various manufacturers displayed tremendous variability with respect to surface roughness and smoother wires did not always produce less friction.[51]

1.7.3.d Hardness

Previous research has demonstrated that friction and hardness are inversely related due to the stronger atomic bonds within harder materials which increase the resistance to adhesion.[58] This was confirmed with orthodontic materials employing Vickers hardness numbers.[20] It was found that the softer titanium alloy archwires had more friction than the harder stainless steel and chromium-cobalt archwires.[20]

1.7.4 Ligation Force and Type

In the absence of binding between the archwire and bracket, the force of ligation was shown to have a dominant influence on the level of friction in orthodontic appliances.[16,55] It was generally found that a positive linear relationship existed between the force of ligation (acting as the normal force) and the friction at the bracket-archwire interface.[20,21,46,59]

Various methods of ligation have been investigated to determine their influence on frictional resistance. One of the difficulties with investigating this effect, however, was controlling the ligation force of the various ligatures. Efforts to reduce this variability were made by using ligature pliers modified with a strain gauge which produced a digital readout.[60] Using this method, it was found that Teflon-coated stainless steel ligatures produced the least friction, followed by conventionally tied elastomeric modules and stainless steel ligatures respectively.[60] Defranco *et al.*, (1995) found similar results.[19] Other studies reported that using elastomeric modules in a figure 8 configuration produced the greatest frictional resistance, and resulted in frictional increases of 70 to 220 percent depending on the dimensions of the archwire used.[54,60,61] No significant trend in frictional resistance was observed when conventionally tied elastomeric ligatures were compared with stainless steel ligatures tightened with 7 turns.[45] Similarly, insignificant differences were found when stainless steel ligatures applying a force of 225 g were compared to elastomeric ligatures.[16] The use of loosely tied stainless steel ligatures resulted in decreased friction relative to conventional elastomeric ligatures.[14,55] It was demonstrated that the ligation force of elastomeric ligatures could be effectively reduced by prestretching them.[32] One study also demonstrated that the frictional resistance using elastomeric ligation changed with time.[55] Initially, rectangular wires had increased friction relative to round wires when elastomeric ligatures were used. Three weeks after the initial placement, however, the friction of rectangular wires dropped significantly and similar forces between round and rectangular wires were observed.[55]

Several orthodontic bracket manufacturers have introduced new bracket designs aimed at minimizing the ligation force in order to decrease the frictional resistance of sliding mechanics (Rocky Mountain Orthodontics, Denver, Colorado; American Orthodontics, Sheboygan, Wis.; GAC, Central Islip, N.Y.). The inter-tiewing span of these new bracket designs is decreased so that the tension of the elastomeric ligatures would be reduced, thus decreasing the normal load at the bracket-archwire interface. Research investigating these brackets found that the limited force of ligation did result in decreased friction.[33] This effect was negated, however, once binding forces were introduced by varying the vertical alignment of adjacent brackets.[33]

The introduction of interactive/self-ligating brackets has also influenced the frictional force produced by orthodontic appliances. These brackets have an internal engaging precision arm which locks the archwire into position as opposed to the conventional twin designs which employ stainless steel or elastomeric ligation. They can be further classified as either active or passive. Active brackets are characterized by a precision arm which partially extends into the wire slot and produces a low seating force on the archwire. Passive interactive brackets, on the other hand, have rigid precision arms which do not extend into the slot and result in minimal seating of the archwires.[61] Examples of active interactive brackets include Sigma (American Orthodontics, Sheboygan, Wis.) and SPEED (Strite Industries Ltd., Cambridge, Ontario). Activa (A-Company, San Diego, California), Interactwin (Ormco Corp., Glendora, California) and Damon (A-Company, San Diego, California) represent passive interactive appliance systems. Interactwin, Damon and Sigma represent interactive versions of conventional twin brackets, whereas Activa and SPEED represent unique interactive designs.

Several investigators have studied the frictional resistance of these various bracket designs. The Activa bracket had less friction than both conventional brackets ligated with elastomeric modules and SPEED brackets.[31,54,55,62] More specifically, the Activa appliance had fifteen times less friction than SPEED and a forty-fold decrease in friction relative to conventional brackets.[54] Some researchers found that SPEED demonstrated less friction than conventional brackets when both rectangular and round archwires were used while others found that only round wires resulted in reduced friction.[54,55,63] When second order angulations were introduced, it was found that SPEED brackets did not produce less friction than conventional brackets tied with either elastomeric modules or slightly slackened stainless steel ligatures.[14] The frictional resistance of the interactive twin brackets was less than their conventional twin counterparts.[61] This was attributed to the decreased coefficient of friction of the stainless steel precision arms relative to elastomeric ties and the low seating force associated with these brackets. Active interactive brackets had more frictional resistance than passive interactive brackets due to the resilient spring design which directed the archwire to the base of the slot resulting in increased normal forces at the bracket-archwire interface.[54,61,62]

1.7.5 The Point of Application of The Retraction Force

The point of application of the retraction force on the bracket had a significant influence on frictional resistance. Studies showed that a more cervical point of application resulted in a decrease in friction.[44,50] The higher friction associated with a more occlusally positioned force was a consequence of the increased binding between the bracket and archwire secondary to the larger moments created.[50]

1.7.6 Intraoral Variables

1.7.6.a Fluid Media

Several researchers have investigated the friction of orthodontic appliances under fluid media in order to simulate the oral environment more closely. Various experiments using artificial saliva and water demonstrated that they may act as both a lubricant and an adhesive. While some researchers found that water and artificial saliva reduced the friction of stainless steel brackets coupled with various archwires from 15 % to 60.5%, others reported that artificial saliva appeared to have an adhesive effect.[28,32,38,42,56,59,64,65] It was postulated that the increased friction recorded for some combinations involving sapphire and ceramic brackets in the presence of artificial saliva may be due to the chemical structure of these brackets.[32] Corrosion was also implicated as the cause of increased friction in water.[53]

Studies investigating the effect of human saliva on frictional resistance recorded different results from those utilizing other fluid media. An earlier study found that human saliva did not influence friction.[26] Recent studies, however, found that saliva increased the friction of stainless steel and cobalt-chromium archwires, but decreased the friction of nickel titanium and TMA wires in conjunction with both stainless steel and ceramic brackets.[20,21,66] TMA demonstrated the greatest reduction of up to 50 percent.[21] Similar results were observed with zirconia brackets coupled with TMA wires.[46] It was suggested that saliva increased the adhesiveness of stainless steel and cobalt-chromium wires by breaking down their oxide layers (corrosion), while it provided a lubricant film for nickel titanium and TMA archwires.[21] Human saliva also appeared to increase the friction of elastomeric and stainless steel ligatures while it decreased the friction of Teflon-coated stainless steel ligatures.[60] An investigation comparing the effect of various fluid media on the friction of orthodontic appliances concluded that artificial salivas resulted in much larger coefficients of friction than human saliva and therefore should not be used to simulate the oral environment.[5]

1.7.6.b Forces Associated with Oral Functions

The oral cavity is a very dynamic environment as it is involved with the processes of speech, swallowing and mastication. These oral functions may cause instantaneous archwire deflections, via food particles and soft tissue contact, which could alter the forces present at the bracket-archwire interfaces in orthodontic appliances. As a means of simulating the dynamic nature of the oral cavity, forces were applied to various components of an orthodontic appliance and the influence on friction was monitored.[67] It was reported that the majority of perturbations resulted in a complete and momentary reduction of frictional forces.[67]

1.7.6.c Biological Resistance

One of the contributors to the frictional forces of orthodontic appliances is the resistance offered by periodontal tissues during tooth movement.[15,50] In order to simulate these forces, several researchers included retarding forces in their experimental design and assessed its influence on frictional resistance. It was generally reported that the frictional force increased with an increase in the retarding force.[15,49,50]

1.8 Corrosion of Orthodontic Appliances

When stainless steel interacts with oxygen a passivated layer consisting of chromium oxide and chromium hydroxide is produced on the surface of the metal. This protective layer provides the corrosion resistance of stainless steel. When the integrity of this layer is undermined or broken down, metal ions from the stainless steel are released and corrosion occurs.[35] Various types of corrosion have been implicated: crevice corrosion, pitting corrosion due to halide ions, galvanic corrosion and intergranular corrosion due to excessive heating. Crevice corrosion has been the suggested mechanism for the corrosion of orthodontic brackets.[68] An acidic chloride environment which is reducing in nature diminishes the stability of the stainless steel oxide film and consequently facilitates corrosion.[69] The oral cavity may therefore potentiate corrosion due to factors such as temperature, the pH of plaque, the chloride in saliva, the physical and chemical properties of nutrition and general oral health.[35,70]

The corrosion of orthodontic appliances has been receiving increased awareness due to the staining of brackets, enamel and bonding resin and the escalating awareness of nickel-sensitive patients in orthodontic practices.[70-73] Stainless steel orthodontic appliances contain approximately 18% chromium and 8% nickel and it has been demonstrated that these elements are released from the metal as a result of corrosion and biodegradation.[35,69,74,75,76]

One investigator noticed that some orthodontic patients presented with black and green stained bracket bases, bonding resin and enamel.[70] Analysis of the discolored resin from the debonded brackets indicated that chromium, iron, nickel and chlorine were present. It was therefore concluded that the corrosion of the stainless steel brackets resulted in the leaching of chromium and nickel into the resin. These ions then formed nickel and chromium chlorides, with chlorine from the saliva, and imparted their characteristic greenish-black color. Furthermore, SEM investigation of these brackets revealed some metal destruction which was suggestive of corrosion.[70]

Several experiments demonstrated that stainless steel orthodontic appliances stored in a sodium chloride solution released nickel and chromium.[35,74,77] The majority of nickel remained in solution whereas the bulk of the chromium precipitated out and both levels plateaued after 6 days.[35] It was also found that brackets with solder joints released more nickel.[74] One study found that chromium-cobalt wires were the only archwires to release nickel or chromium.[74] This was in accordance with Edie *et al.* (1981) who found no evidence of corrosion pits on stainless steel or Nitinol wires under clinical conditions.[78] Nitinol did show evidence of corrosion, however, under cyclic polarization while chrome-cobalt, stainless steel and beta-titanium wires remained passive.[77] Heat treating chrome-cobalt and stainless steel wires above 400 degrees Celsius, however, impaired the passivity of these wires.[79] The influence of an "oral functioning simulator" was used to study the effect of movement on the release of nickel and chromium from a quadrant of orthodontic appliances with a nickel-titanium archwire in a 0.9% sodium chloride solution.[75] It was found that significantly more nickel was released under a dynamic situation; whereas the release of chromium was not affected. It was calculated that four quadrants of appliances would release 40 μg of nickel and 36 μg of chromium daily. These values are much less than the average dietary intake of these two metals: 200-300 μg/day for nickel and 280 μg/day for chromium.[35]

The biodegradation of stainless steel brackets and bands in conjunction with stainless steel and nickel titanium archwires was investigated using artificial saliva.[76] It was found that the maximum nickel released from the appliances due to corrosion peaked after 7 days and then declined steadily for both groups of appliances. The release of chromium, on the other hand, peaked after 14 days in the appliances with nickel titanium wires, while it increased steadily to the 28th day in the appliances tied with stainless steel archwires.

1.9 Summary of Introduction

The importance of friction and corrosion of orthodontic appliances is evident through the extensive research investigating these properties. Numerous studies demonstrated that several bracket and archwire properties influenced the frictional resistance inherent in sliding mechanics. A few years ago, a new titanium bracket, Rematitan, was introduced by Dentaurum Inc. (Pforzheim, Germany). Since previous research indicated that the compositions of the brackets and archwires influenced the efficiency of orthodontic appliances, this study compared the frictional resistance of stainless steel and titanium brackets paired with stainless steel and beta-titanium (TMA) archwires. These tests were also performed in the presence of saliva to assess its influence, and that of stress corrosion, on the friction between these orthodontic brackets and archwires.

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Chapter 2

Research Paper

The Friction and Wear Patterns of Orthodontic Brackets and Archwires in the Dry State.

2.1 Introduction

The frictional resistance encountered during sliding mechanics has been well established in the orthodontic literature and it consists of complex interactions between the bracket, archwire and method of ligation. Tooth movement associated with sliding mechanics has been described as a series of short steps involving oscillating tooth tipping and uprighting, rather than a continuous, smooth, gliding-like process.[1-4] The overall resistance to sliding in orthodontic appliances is a combination of classical friction, archwire-bracket binding and archwire notching.[5] At a minimal bracket-archwire angulation and torque, friction is mainly due to classical friction, whereas binding and notching become more prominent at large bracket-archwire angulations. As the friction at the bracket-archwire interface increases, the proportion of the applied force that is actually transmitted into tooth movement decreases. This results in a less efficient orthodontic appliance.[5]

The impact of many factors on the friction encountered with orthodontic appliances has been established and their influences have been assessed (Table 2-1). It was reported that friction increased as the second and third order bracket-archwire angulations increased and the vertical discrepancy between adjacent brackets increased.[3,6-14] It was also shown that wear associated with multiple passes sometimes increased and sometimes decreased the friction of orthodontic appliances and that both adhesive and abrasive wear may occur.[15-18] Stainless steel brackets had less friction than ceramic brackets and the influence of bracket width and bracket surface roughness were variable.[1-4,6,7,9,10,12,15,18-29] Bracket slot size and interbracket distance appeared to have a minimal influence on friction.[3,17] Beta-titanium and nickel titanium archwires generally resulted in less efficient sliding mechanics than stainless steel and chromium-cobalt archwires.[γ] Nickel titanium wires, however, recorded the lowest friction at larger bracket-archwire angulations due to their lower modulus of elasticity.[3,7,12,24] Frictional resistance generally increased with an increase in archwire size and rectangular archwires generally produced more friction than round wires.[ψ] Archwire surface roughness had a variable influence on friction and an inverse relationship between friction and archwire hardness was established.[16-18,32,34,40] The forces of archwire ligation varied with the different ligation options, and a positive linear relationship with frictional resistance was recorded.[1,3,7,30,36,38,41-44] It was also reported that friction decreased with a more cervical point of force application.[37,45] Various fluid media, simulating the oral environment, produced variable results compared to the dry state.[λ] While simulated masticatory forces applied to orthodontic appliances resulted in momentary reductions in frictional force, simulated biological resistances increased friction.[2,28,45,51]

Orthodontic practitioners have been aware of the importance of the above interactions and thus considerable research is undertaken with the aim of developing more efficient orthodontic appliances. One such example is Rematitan, a pure titanium bracket manufactured by Dentaurum Inc. (Pforzheim, Germany). The increased biocompatibility and corrosion resistance of titanium are two characteristics which have been suggested as improvements for Rematitan over the more common stainless steel and ceramic brackets.[52] Since the tribological properties of these brackets in conjunction with

γ 2,9,18-20,23,26,28,30-33

ψ 1-3,6,7,9,11,12,19,20,23,26,28,29,33-39

λ 6,9,18,20,23,24,31,39,42,46-50

various orthodontic archwires have a direct impact on successful orthodontic treatment, it is imperative that the wear and frictional characteristics of these brackets be researched.

The purpose of this study was to investigate and compare the coefficients of friction of titanium brackets with stainless steel brackets (Mini-V Diamond Twin, Ormco Corp., Glendora, California) in conjunction with stainless steel and ion-implanted beta-titanium archwires (TMA, Ormco Corp., Glendora, California). The effect of archwire alloy, dimension and geometry were also studied. The wear patterns of the different bracket and archwire alloys and their association with friction were also investigated.

2.2 Materials and Method

2.2.1 The Testing Apparatus

The testing apparatus used for this investigation was modified from a previous design to accommodate the specific tests (Figures 2-1 and 2-2).[23] The brackets were bonded onto acrylic pedestals which were fastened to an adjustable stage to enable proper bracket positioning beneath the Teflon guide. This guide applied a normal load of 500 grams to the bracket-archwire interface by hanging a brass weight from a cross-beam which was connected to the Teflon guide by a vertical bearing system. An electric motor pulled the archwires across the brackets at a speed of 23 mm/minute via a pillow block, which was connected to the archwires by a thin cable. A load cell, located at the end of the pillow block, recorded the force required to pull the archwires across the brackets. The output of the strain gauge conditioner, which was connected to the load cell, was calibrated to provide an output of 1 mV/1 gram. The load cell readings were recorded by a computer for the duration of the test.

2.2.2 Preparation of the Bracket and Archwire Samples

Titanium (Ti) mandibular incisor brackets and stainless steel (SS) maxillary central incisor brackets were tested in conjunction with .016 X .022 inch rectangular and .020 inch round stainless steel (SS) archwires as well as .016 X .022 inch rectangular TMA archwires (Table 2-2). In order to calculate the coefficient of friction, the normal force and the frictional force between the two surfaces must be known. These are related by the equation:

$$\mu = \frac{F}{N} \qquad (2\text{-}1)$$

where μ represents the coefficient of friction, F is the frictional force and N represents the normal force at the interface between the surfaces.[53] Pulling the archwire through the bracket slot would normally result in multiple surface contacts and normal forces between them, thereby increasing the complexity in calculating the coefficient of friction. Therefore, this study was designed to ensure a single surface contact interface with a constant normal force between the brackets and archwires. In order to achieve this, the vertical inter-wing surface of the stainless steel brackets[23] and the lateral surface of the titanium brackets were utilized in conjunction with the .020 inch round stainless steel archwires and the individual .016 inch and .022 inch flat surfaces of the rectangular stainless steel and TMA archwires. The laser markings on the vertical inter-wing surface of the titanium brackets precluded the use of this surface for the testing procedure. Since the slot surfaces are not preferentially treated, using different testing surfaces for the titanium and stainless steel brackets would not influence the testing results. The wings of the stainless steel brackets were removed using wire cutting pliers and any remaining metal spurs were removed with a highspeed bur so they would not interfere with the Teflon guide during the testing procedure.[23]. Visual inspection ensured that the testing surface was not altered during this procedure.[23] Hooks were formed at one end of each 35 mm segment of straight archwire to provide an attachment to the motor-pulley system described below.

2.2.3 The Testing Procedure

Twelve independent samples of each bracket-archwire combination were tested and each test involved a new bracket and archwire. This resulted in a total of 120 samples tested in random order. The brackets were bonded onto acrylic testing bases and cleaned with 95% ethanol. The archwire samples were also cleaned with 95 % ethanol and stored in a desiccator for one hour to ensure an uncontaminated testing surface. Latex gloves and cotton pliers were used to mount and align the samples to prevent contamination of the testing surfaces. The brass weight was then attached below the adjustable stage to provide the 500 gram load at the interface. Ten millimeters of archwire were pulled across the bracket surface and the load cell output was recorded and stored in the computer. The force readings were plotted using Microsoft Excel 5.0 (Microsoft, U.S.A.) as shown in figure 2-3. The load recorded at the initial peak represented the value of static friction. The kinetic friction was determined from the mean of the load cell output values recorded for a duration of 25 seconds, starting 0.5 seconds after the initial static peak. The coefficients of friction were calculated from the recorded frictional forces using equation 2-1, and they are listed in table 2-3.

Since a Teflon guide was used to direct the wires across the brackets and apply the normal load, the force recorded by the load cell included the frictional resistance of the bracket-archwire interface and the Teflon guide-archwire interface. The results obtained, therefore, represent comparative findings, rather than absolute frictional resistances between the brackets and archwires. Teflon, which is known to have reduced friction,[54] was used so that the bracket-archwire interface would account for the majority of the frictional resistance recorded by the load cell. In order to determine the contribution of the Teflon-archwire frictional resistance to the overall force recorded by the load cell, the coefficients of friction between the Teflon guide and each archwire type were measured. This was accomplished by pulling fifteen samples of each wire type between two Teflon guides and dividing the recorded frictional force in half. The coefficient of friction means and standard deviations of the various Teflon-archwire interfaces were calculated (Table 2-4). These values were then subtracted from the corresponding bracket-archwire coefficient of friction means (from table 2-3) in order to isolate the coefficients of friction of the various bracket-archwire interfaces. These adjusted means and standard errors appear in table 2-5. The friction recordings of the individual bracket-archwire samples could not be adjusted since it was not possible to account for the variation of the Teflon–archwire interface with those values.

In addition to the friction testing, the wear patterns of the archwire-bracket combinations involving the .016 inch surface of the TMA and stainless steel archwires were investigated using an Hitachi S-2700 scanning electron microscope (SEM) equipped with a Link eXC energy dispersive x-ray analyser (EDX). The orientation of the brackets on the micrographs is shown in figure 2-4. Pretest scanning electron micrographs of the bracket surfaces and the archwire surfaces (at the center of the testing length) were obtained to establish their initial surface properties. After testing, SEM analyses were repeated and regions of wear were examined under a higher magnification (Figures 2-5 to 2-8). Energy dispersive x-ray analysis was used to analyze the composition of the particles transferred between the archwires and brackets. The micrographs were then categorized, without knowing which bracket-archwire couple they represented, according to the different wear patterns outlined in tables 2-6 and 2-7.

2.2.4 Statistical Analysis

In order to compare the frictional resistances of the different bracket alloys, archwire alloys, archwire dimensions and archwire configurations, it would be ideal to compare the adjusted coefficient of friction means (from table 2-5) with either a t-test or a Kruskal-Wallis One-Way Anova. These adjusted values, however, did not satisfy the requirements for these tests. The t-test is a parametric test and is therefore indicated when the variances and standard deviations between the different groups are similar.[55] Since the standard deviations between some groups were quite different, the *p*-values would be misleading. The Kruskal-Wallis One-Way Anova (a non-parametric test) could not be performed because the adjusted frictional coefficients for the individual samples, which are normally required, could not be calculated as mentioned previously. Thus, the recorded coefficient of friction means from table 2-3 (which includes the friction of the Teflon guide) were used for the statistical analyses (Tables 2-8 to 2-24 and Tables 2-26 to 2-28, Figures 2-9 to 2-16).

The coefficient of friction means of the various bracket alloys, archwire alloys, archwire sizes and archwire geometries were compared to determine whether they differed significantly with a p-value (one-sided) < 0.05. It was apparent from table 2-3 and from the boxplots of the coefficients of friction (Figures 2-9 to 2-16) that the standard deviations and distributions of all the bracket-archwire combinations were not similar. Logarithmic and square root transformations were therefore performed in an attempt to reduce this discrepancy which would enable the use of t-tests for all comparisons. These transformations, however, were unsuccessful at achieving this for all subgroups. Consequently, either a t-test or a Kruskal-Wallis One-Way Anova was performed, depending on the ratio of the standard deviations of the groups being compared. A ratio of 1.5 was used as a guideline to differentiate similar and variable standard deviations. The Kruskal-Wallis One-Way Anova was employed when the ratio of the larger standard deviation to the smaller standard deviation was greater than 1.5. A t-test was performed when the ratio of the standard deviations was less than 1.5. A t-test using the transformed data was employed when the corresponding standard deviations led to a further reduction in the ratio.

A chi-square test (Table 2-25) was used to assess the association between bracket wear and archwire wear and the different archwire-bracket combinations. The association between bracket wear and bracket alloy, and archwire wear and archwire alloy were also determined with a chi-square test. A Kruskal-Wallis One-Way Anova was used to compare the coefficient of friction means of the various wear categories. This non-parametric test was used due to the varying standard deviations among the groups.

2.2.5 Method Error

The samples were tested in random order to minimize the influence of experimental error on the test results. The reliability of the load cell was established by recording the load cell output when 100, 200, 300 and 400 gram brass weights were attached to the load cell and repeated 10 times. The means and standard deviations were calculated and the reliability coefficient (Cronbach's Alpha) of the repeated measures was determined to assess the internal consistency of the load cell. The consistency of the bracket wear and archwire wear categorization techniques was established by performing them a total of five times and determining the reliability coefficient (Cronbach's Alpha) for the repeated categorizations.

2.3 Results

2.3.1 Bracket Alloy: Titanium vs. Stainless Steel Brackets

The coefficients of static and kinetic friction of the stainless steel brackets were significantly less ($p < 0.05$) than titanium brackets when all samples were included (Table 2-8). When the coefficients of friction were compared for each individual wire, however, not all differences were significant (Figures 2-9 and 2-10, Tables 2-9 and 2-10). Stainless steel brackets had significantly lower coefficients of static and kinetic friction ($p < 0.05$) with all wires except stainless steel .020 inch round wires. The decreased static friction of stainless steel brackets relative to titanium brackets was particularly noted with TMA archwires.

2.3.2 Archwire Alloy: Stainless Steel versus TMA Archwires

Stainless steel archwires demonstrated significantly lower coefficients of static friction ($p < 0.05$) than TMA archwires for each individual archwire size and bracket combination as well as when all the subgroups were compared collectively (Figure 2-11, Tables 2-11 and 2-12). Similarly, the coefficient of kinetic friction of stainless steel archwires was significantly less ($p < 0.05$) for all situations with the exception of .022 inch flat archwire surfaces tested with stainless steel brackets (Figure 2-12, Tables 2-11 and 2-13).

2.3.3 Archwire Dimension: .016 inch versus .022 inch Flat Archwire Surfaces

When all the subgroups were compared collectively there was no significant difference between the coefficients of static friction for the two archwire surfaces (Table 2-14). When the coefficients of static friction were compared for each bracket-archwire combination, however, the .022 inch surfaces had significantly more ($p < 0.05$) friction than the .016 inch surfaces for stainless steel wires tested with titanium brackets. The reverse was recorded with TMA wires coupled with titanium brackets (Table 2-15). The coefficient of kinetic friction of the .016 inch surface was significantly greater ($p < 0.05$) than the .022 inch flat surface when all subgroups were compared collectively and when TMA wires were tested with both brackets (Tables 2-14 and 2-16).

2.3.4 Archwire Geometry: Round versus Flat Stainless Steel Archwire Surfaces

The coefficient of kinetic friction of the .016 inch flat archwire surfaces was significantly greater ($p < 0.05$) than the .020 inch round wires (Figure 2-16, Tables 2-17 and 2-19). No significant difference was found, however, between the static coefficients of friction of these wires (Figure 2-15, Tables 2-17 and 2-18). The .022 inch flat archwire surfaces also demonstrated significantly larger ($p < 0.05$) coefficients of kinetic friction than the .020 inch round wires when the tests with both bracket alloys were combined (Table 2-20) and separated (Table 2-22). The coefficients of static friction of the .022 inch surfaces was larger when the results from both brackets were combined ($p < 0.05$) and when tested with titanium brackets (Table 2-21).

2.3.5 Wear Study

The coefficient of friction means and the distribution of bracket wear and archwire wear for each archwire-bracket couple are shown in tables 2-23 and 2-24. The bracket wear patterns and archwire wear patterns varied significantly ($p < 0.05$) with the different bracket-archwire combinations, bracket materials and archwire alloys (Table 2-25). Tables 2-26 and 2-27 display the coefficient of friction means for each bracket wear and archwire wear category. The coefficient of friction means of the bracket wear patterns were significantly different ($p < 0.05$) with mild abrasion having the lowest values and adhesion with moderate abrasion demonstrating the highest static frictional coefficient (Table 2-28). The coefficient of friction means for the categories of archwire wear were also significantly different ($p < 0.05$) with mild abrasion demonstrating the lowest values and adhesion with severe abrasion recording the largest values (Table 2-28).

The most common wear pattern involving stainless steel brackets with stainless steel archwires was mild abrasive bracket wear in conjunction with mild abrasive archwire wear and adhesion (Tables 2-23 and 2-24, Figure 2-5). The majority of samples involving titanium brackets and stainless steel wires demonstrated severe abrasive bracket wear and mild archwire abrasion with titanium cold welding to the wires (Tables 2-23 and 2-24, Figure 2-6). The stainless steel brackets tested with TMA archwires demonstrated TMA adhesions with mild bracket abrasion (Table 2-23, Figure 2-7). The corresponding archwires generally displayed severe abrasion with TMA particles (Table 2-24, Figure 2-7). The titanium brackets tested with TMA wires generally demonstrated severe abrasive wear with adhesion while the wires exhibited severe abrasion with adhesion (Tables 2-23 and 2-24, Figure 2-8).

2.3.6 Method Error

The results of the load cell reliability test are outlined in table 2-29. Because the standard deviations were similar among the different masses and the load cell demonstrated high reliability (Alpha = 0.9917), experimental error had a minimal influence on the range of variances recorded among the different bracket-archwire combinations. The archwire categorization technique was highly reliable (Alpha = 0.9605). Thus, the most common archwire wear pattern for each bracket-archwire combination was used for the statistical analyses. A reliability analysis was not required for the bracket wear categorization technique since all five trials produced identical results.

2.4 Discussion

The results of this study indicate that stainless steel brackets combined with the .016 inch flat stainless steel wire surfaces represented the lowest coefficient of static friction while titanium brackets in conjunction with stainless steel .020 inch round archwires measured the lowest kinetic friction. The highest frictional resistance was recorded with the .016 inch flat TMA archwire surfaces tested with titanium brackets. This combination resulted in a twofold increase in static and kinetic friction over the most efficient combinations. Stainless steel brackets were associated with significantly less static and kinetic friction than titanium brackets for all archwires except the .020 inch round stainless steel wires. The largest difference was noted with TMA archwires. The lack of statistical significance with the round archwires may be attributed to the absence of edges, which may have minimized the amount of plowing otherwise noted with the .016 inch flat surfaces under the SEM.

With respect to the archwire alloys, stainless steel archwires had significantly lower coefficients of static friction and kinetic friction than TMA wires in agreement with several previous studies.[2,16-19,23,26,28,30-34,50] One exception, however, was observed with the .022 inch flat wire surface in conjunction with stainless steel brackets. The high variability of the TMA wires may account for the lack of a significant difference between the kinetic friction means of the two alloys.

An overall aim of this study was to investigate the tribological properties of orthodontic appliances. In particular, the association between wear, friction and the various bracket and archwire materials was of interest. The distribution patterns of the wear counts for the four bracket-archwire combinations, outlined in tables 2-23 and 2-24, display how the bracket and archwire wear patterns varied significantly with the various bracket-archwire combinations. The stainless steel bracket - stainless steel archwire combination recorded the lowest frictional means and was associated with mild and moderate abrasive bracket wear with the majority of the wires demonstrating mild abrasion with adhesion. The titanium bracket - TMA wire couple demonstrated the highest frictional values and was associated with moderate to severe bracket abrasion with TMA adhesions, while the archwires demonstrated severe abrasion with adhesion.

The coefficients of friction of the different wear patterns were also significantly different ($p < 0.05$), indicating an association between wear and friction. A general pattern between increasing bracket abrasion and increasing coefficients of friction is apparent in table 2-26 with the exception of moderate abrasion and severe abrasion in conjunction with adhesion. The length of the wear track on the bracket surface distinguished these two patterns, which were exhibited by titanium brackets exclusively.

The increased static friction of moderate abrasion relative to severe abrasion may suggest that the brackets and archwires were not perfectly parallel thereby resulting in one of the bracket edges being more prominent. This may have simulated archwire to bracket binding which has been implicated as an important contributor to friction.[3,5]

The general trend of increased friction of the titanium brackets is also reflected in the increased frictional coefficient means of the wear patterns displayed by these brackets. Although both bracket types demonstrated adhesion with TMA wires, the titanium brackets exhibited moderate or severe abrasion, while the stainless steel brackets exhibited mild abrasion. The titanium brackets also demonstrated more severe abrasion than stainless steel brackets when they were tested with stainless steel archwires. The prominent abrasive wear tracks and increased coefficients of friction of titanium brackets suggest that the titanium brackets are softer than the stainless steel brackets since friction and hardness are inversely related.[56] The oxide layer on the surface of metals provides a protective film and prevents adhesion as long as it is not penetrated.[57] It appears, that the oxide layer of titanium brackets was not beneficial for improving orthodontic sliding mechanics since severe abrasion and cold welding were evident with both TMA and stainless steel wires.

While both stainless steel and TMA archwires tended to demonstrate adhesive wear, the abrasive wear observed on the TMA archwires was generally more severe than that observed on the stainless steel wires. Furthermore, the archwire wear group representing the majority of TMA wires (adhesion and severe abrasion) had a two fold increase in friction over the archwire wear patterns demonstrated by the stainless steel wires (mild abrasion without adhesion and mild abrasion with adhesion). This explains the increased friction associated with TMA wires. EDX confirmed that the adhesive particles present on the TMA archwires after testing were from the archwire itself and not from the titanium or stainless steel brackets. This suggests that when cold welding occurred between the brackets and TMA archwires, the adhesive junction was stronger than the internal strength of the TMA wire.[57] Thus, shearing occurred within the TMA and wear particles from the wire were produced resulting in a three-body abrasive wear system. With further archwire sliding, these particles readhered to the TMA surface.

When stainless steel wires were slid across titanium brackets, titanium adhesions were detected on the stainless steel wires. This suggests that the cohesive forces within the titanium were inferior to the adhesive strength of the stainless steel-titanium junctions. Since this is opposite to the material transfer seen with TMA wires, this confirms a previous finding that TMA wires are softer than stainless steel wires.[18] The friction plots of the TMA wires appeared to demonstrate larger oscillations in frictional force than those of the stainless steel wires as demonstrated in figure 2-17. These fluctuations may be attributed to the forming and breaking of adhesive junctions leading to the increased severity of wear and the higher coefficients of friction associated with TMA wires.[16]

When stainless steel brackets were tested with stainless steel archwires, particles were detected on the wire surfaces but not on the bracket surfaces. Since the brackets and wires are of the same material, EDX was not able to determine the origin of these particles. SEM analyses of the bracket and archwire surfaces did not reveal any pitting which would indicate the origin of these particles. One reason for the absence of these voids may be that they were filled in due to the abrasive wear process occurring with sliding mechanics. These particles may also be the result of adhesions occurring at localized areas of internal weaknesses within the wires resulting from manufacturing defects. If the strength of the adhesive junction exceeded the cohesive strength within the defect, shearing occurred along the weakened internal planes of the wire and resulted in particle formation.

This study also investigated the second law of friction which states that friction is independent of the apparent area of contact.[53,58] Although stainless steel wires were generally in accordance with this law, exceptions were noted with TMA wires. The significantly larger coefficients of friction of the .016 inch surface TMA archwires relative to the .022 inch TMA surfaces may have resulted from slight archwire tilting during the testing, resulting in a prominent edge and increased wear. This edge effect may have been further exacerbated by the increased severity of wear observed with TMA wires.

The orthodontic literature revealed that round wires generally produced less friction than rectangular wires, but some exceptions were noted.[3,6,7,11,12,19,23,33,35,38,39] When comparing round versus rectangular archwires, the occlusogingival wire dimension and the effect of binding must also be considered since larger and stiffer wires would result in larger normal forces at the bracket-archwire interface at binding angulations.[2,3,27] In order to eliminate the possible influence of binding, the design of this study entailed single surface interfaces. The flat stainless steel archwire surfaces had significantly greater coefficients of kinetic friction than the round wires. This suggests that during the sliding process there may have been some archwire tilting which resulted in an edge effect as previously described.

The forces recorded by the load cell in this study represent comparative findings, rather than absolute frictional resistances between the brackets and archwires due to the friction associated with the Teflon guide. When the friction of the Teflon-archwire interface was subtracted from the recorded values the general order of the magnitude of the coefficients of friction was maintained relative to table 2-3. A few changes, however, were noted. Subtracting the friction of the Teflon-archwire interface resulted in equal coefficient of static friction means for the .016 inch and the .022 inch stainless steel archwire surfaces tested with stainless steel brackets. A similar result was seen with .020 inch round wires and the .016 inch flat surface of the stainless steel wires when tested with titanium brackets.

The design of this experiment ensured a single surface contact in order to predictably calculate the coefficients of friction. By doing so, however, it did not replicate the binding that occurs during sliding mechanics. While the normal load applied at the bracket-interface in this study simulated the load when bracket-archwire binding occurs, the pressures between the two situations would not be equal. With bracket-archwire binding, the load is concentrated at opposite edges of the bracket slot and therefore larger pressures would result than those across the larger interface of this study. These increased pressures may result in gouging and notching of the archwire. These phenomena, which were not simulated in this experiment, may reduce the efficiency of orthodontic sliding mechanics and may alter the comparative frictional resistances recorded in this study.

Clinical experience has demonstrated that orthodontic tooth movement occurs at a very slow rate. The mean rate of tooth movement is estimated to be 1 mm/month (2.3 X

10^{-5} mm/min). Although this study calculated both the coefficients of static and kinetic friction, the results from the static frictional coefficients may have a greater significance to the slow and non-continuous tooth movement observed with sliding mechanics.

2.5 Conclusions

The findings from this study indicate that sliding mechanics involving stainless steel or titanium brackets and .020 inch round stainless steel wires had similar frictional resistances. When rectangular stainless steel or TMA wires were used, however, stainless steel brackets had significantly lower coefficients of static and kinetic friction than titanium brackets. TMA wires had greater friction than stainless wires and therefore would result in less efficient sliding mechanics. Titanium brackets coupled with TMA wires recorded the largest frictional resistances and are therefore not recommended for orthodontic sliding mechanics. The increased friction of the TMA wires and titanium brackets was also reflected in the coefficient of friction means of the wear patterns exhibited by these alloys, namely severe abrasion with adhesion. An inverse relationship was generally found between friction and archwire surface dimension for TMA archwires. Round archwires demonstrated lower coefficients of kinetic friction than the flat surfaces of rectangular archwires.

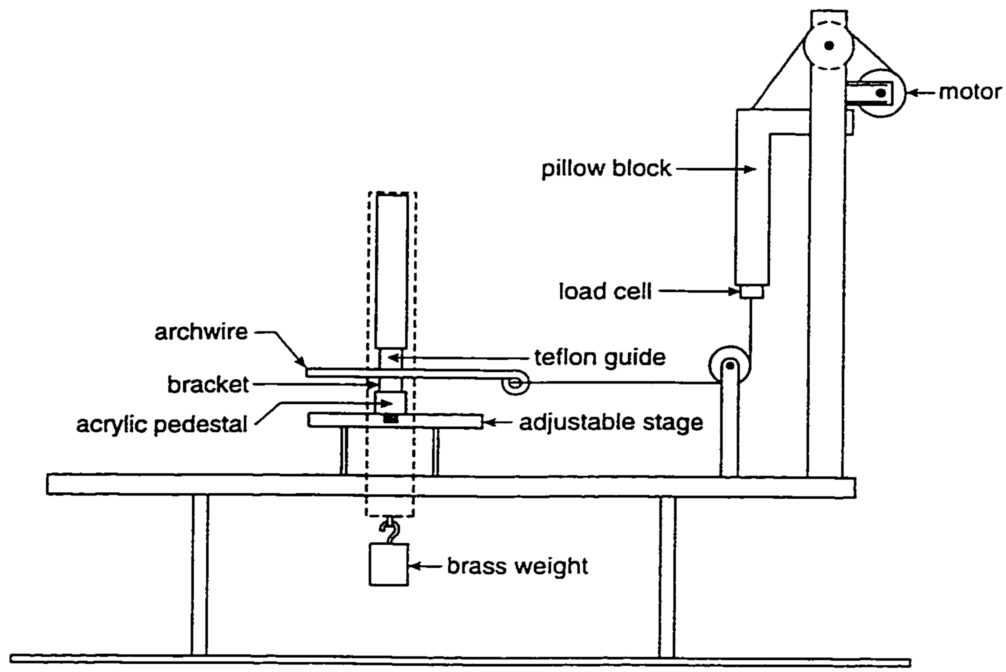


Figure 2-1. A schematic representation of the testing apparatus.

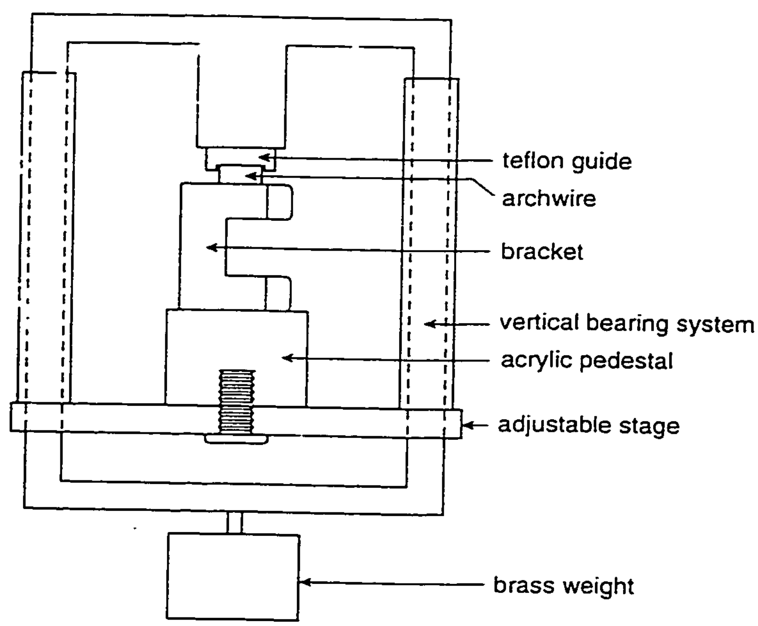


Figure 2-2. A detailed view of the bracket-archwire assembly.

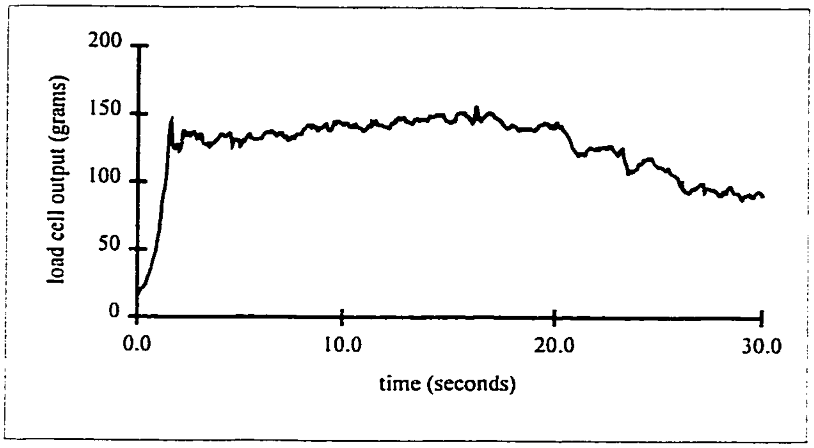


Figure 2-3. A graphical representation of the load cell output.

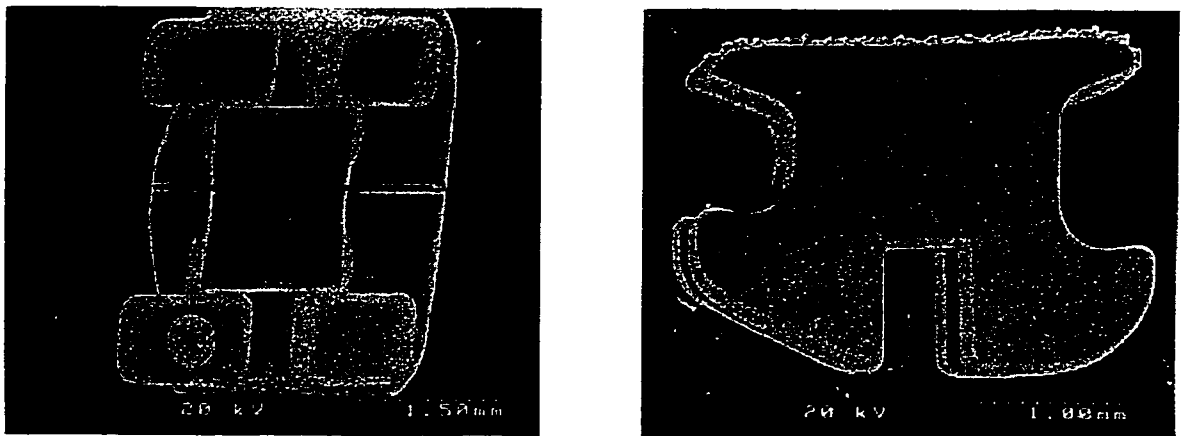


Figure 2-4. SEM images showing the orientation of a stainless steel bracket (right) and titanium bracket (left) with the archwire (as indicated by arrow).

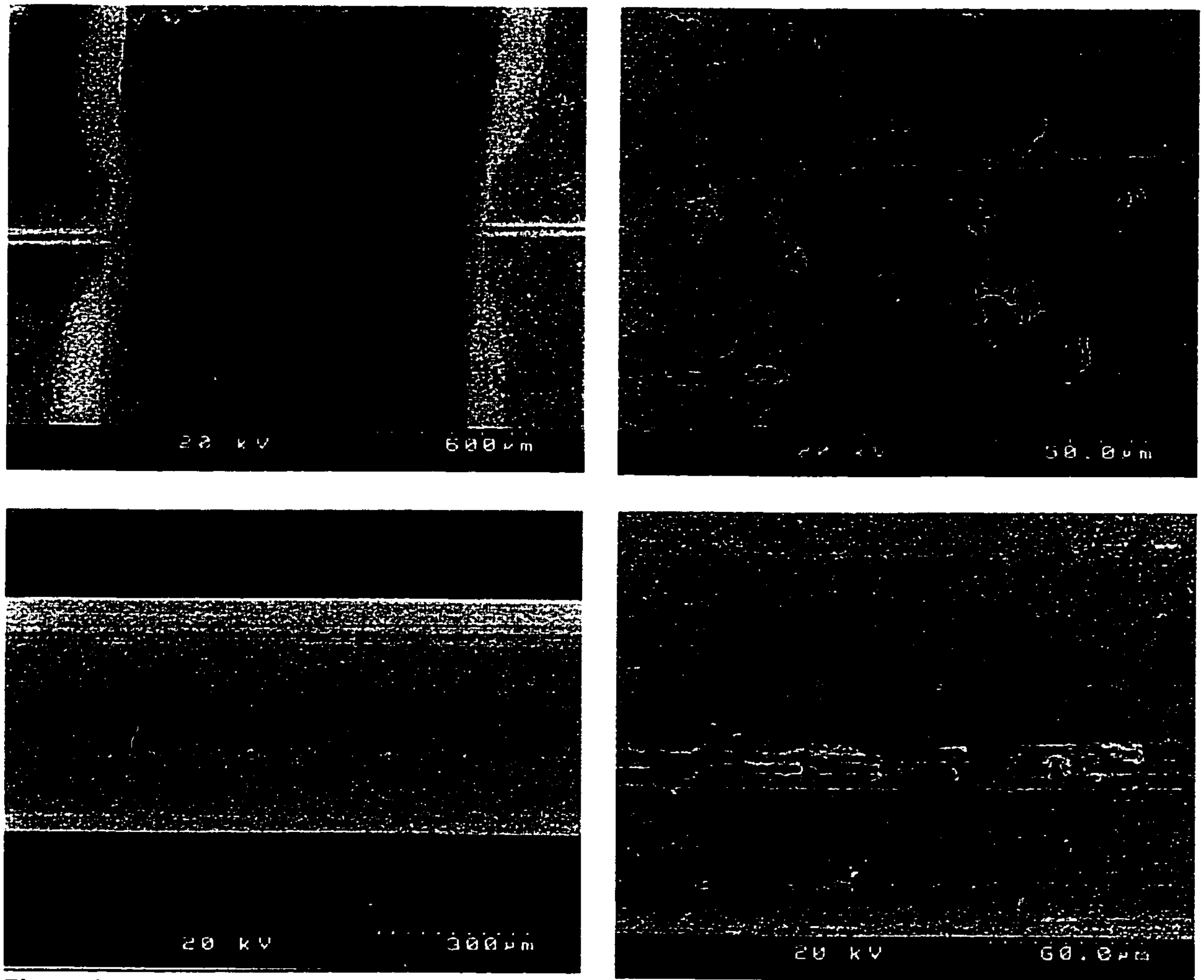


Figure 2-5. SEM images of a stainless steel bracket (top) and stainless steel archwire (bottom) combination. The square areas outlined on the left images are seen under higher magnification on the right. The stainless steel bracket demonstrates mild abrasion as demonstrated by the grooves (G). The stainless steel archwire shows grooves (G) and wear particles (P) which are characteristic of mild abrasion with adhesion.

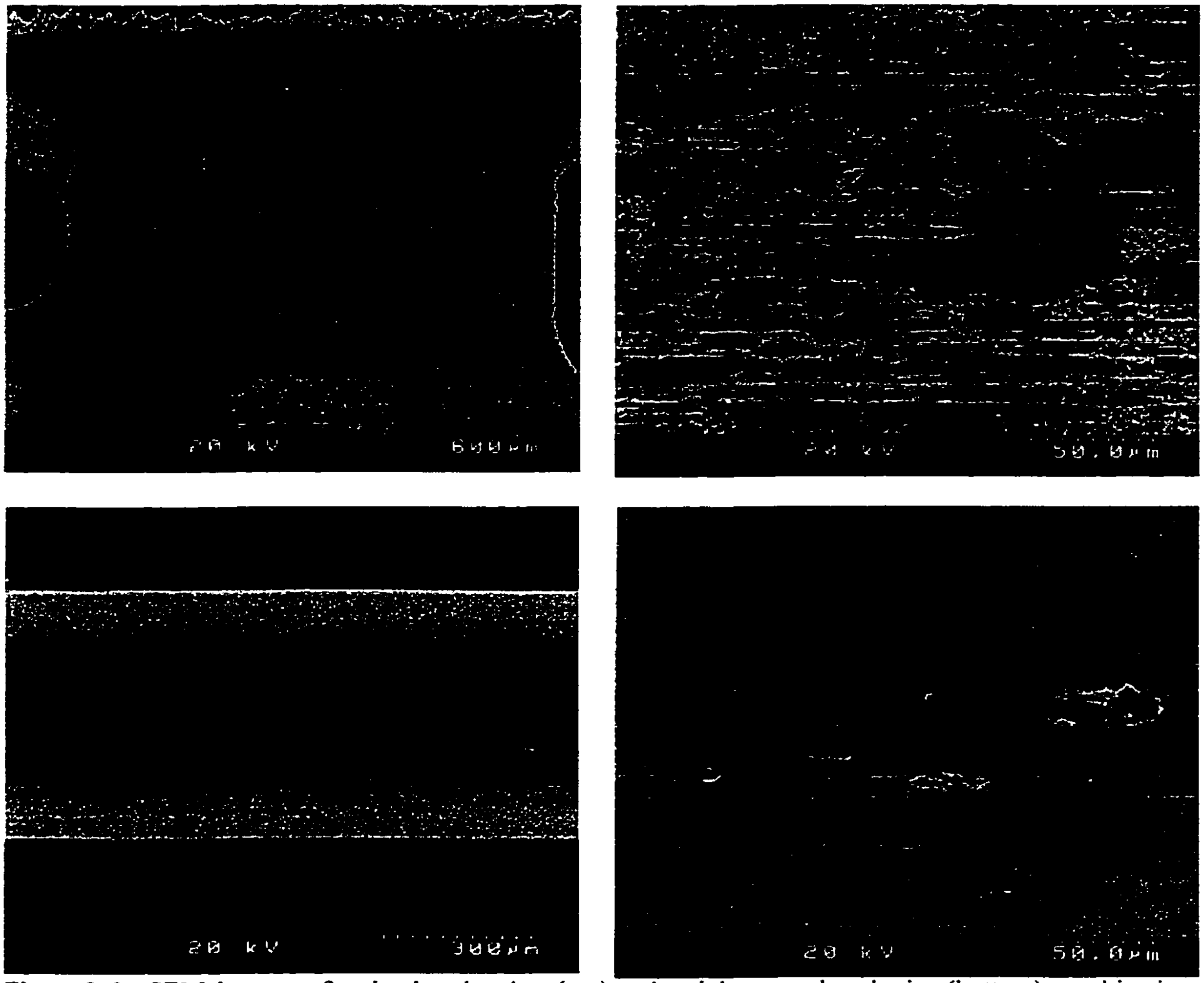


Figure 2-6. SEM images of a titanium bracket (top) and stainless steel archwire (bottom) combination. The square areas outlined on the left images are seen under higher magnification on the right. The bracket demonstrates a wear track (W) and plowing with ribbon-like formations which are characteristic of severe abrasion. The stainless steel archwire shows titanium adhesive particles (P) with grooves (G) which represent mild abrasion with adhesion.

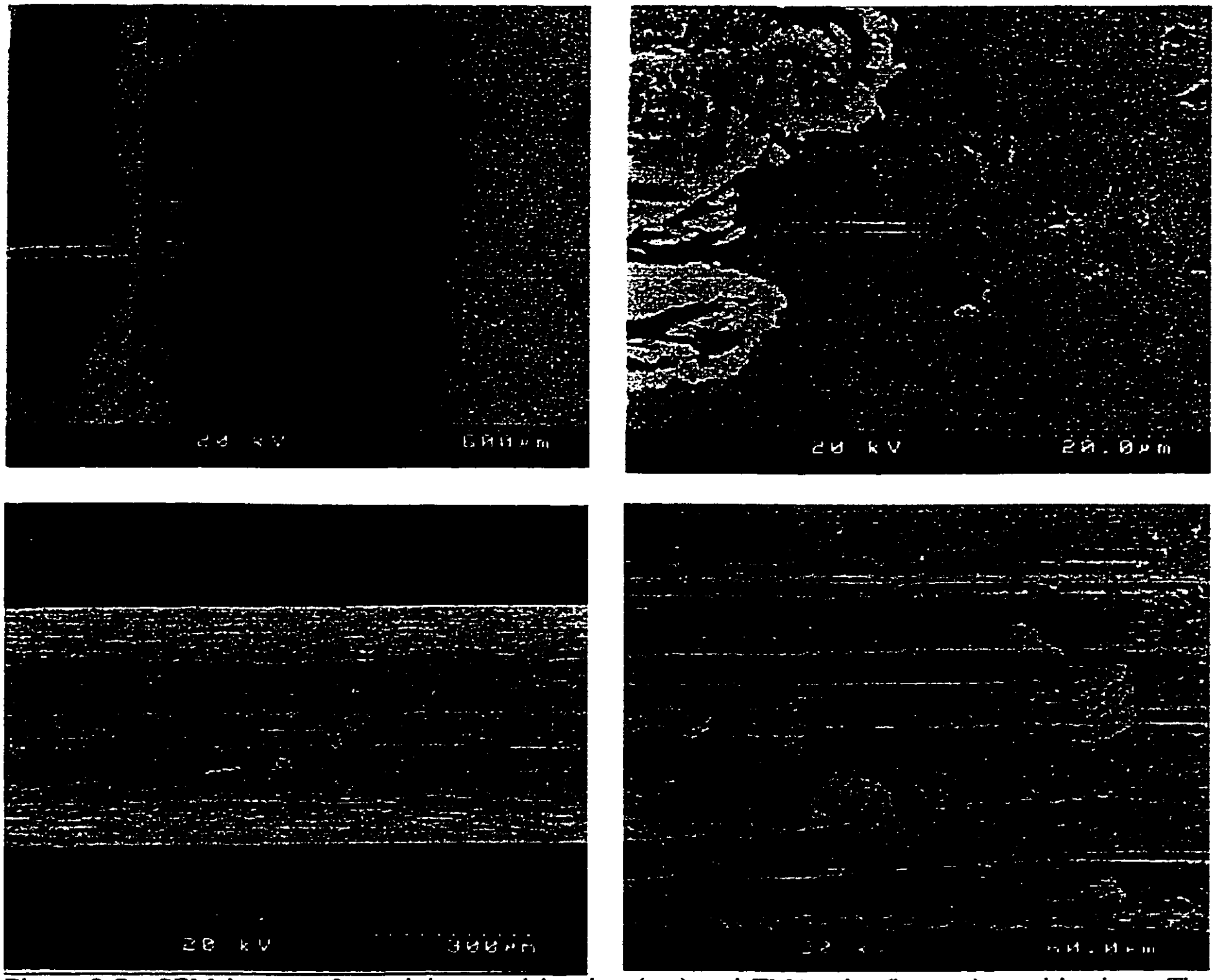


Figure 2-7. SEM images of a stainless steel bracket (top) and TMA wire (bottom) combination. The square areas outlined on the left images are seen under higher magnification on the right. The TMA particle (P) and grooves (G) on the bracket surface represent mild abrasion with adhesion. Plowing of the TMA wire with ribbon-like formations and TMA particles (P) represent severe abrasion with adhesion.

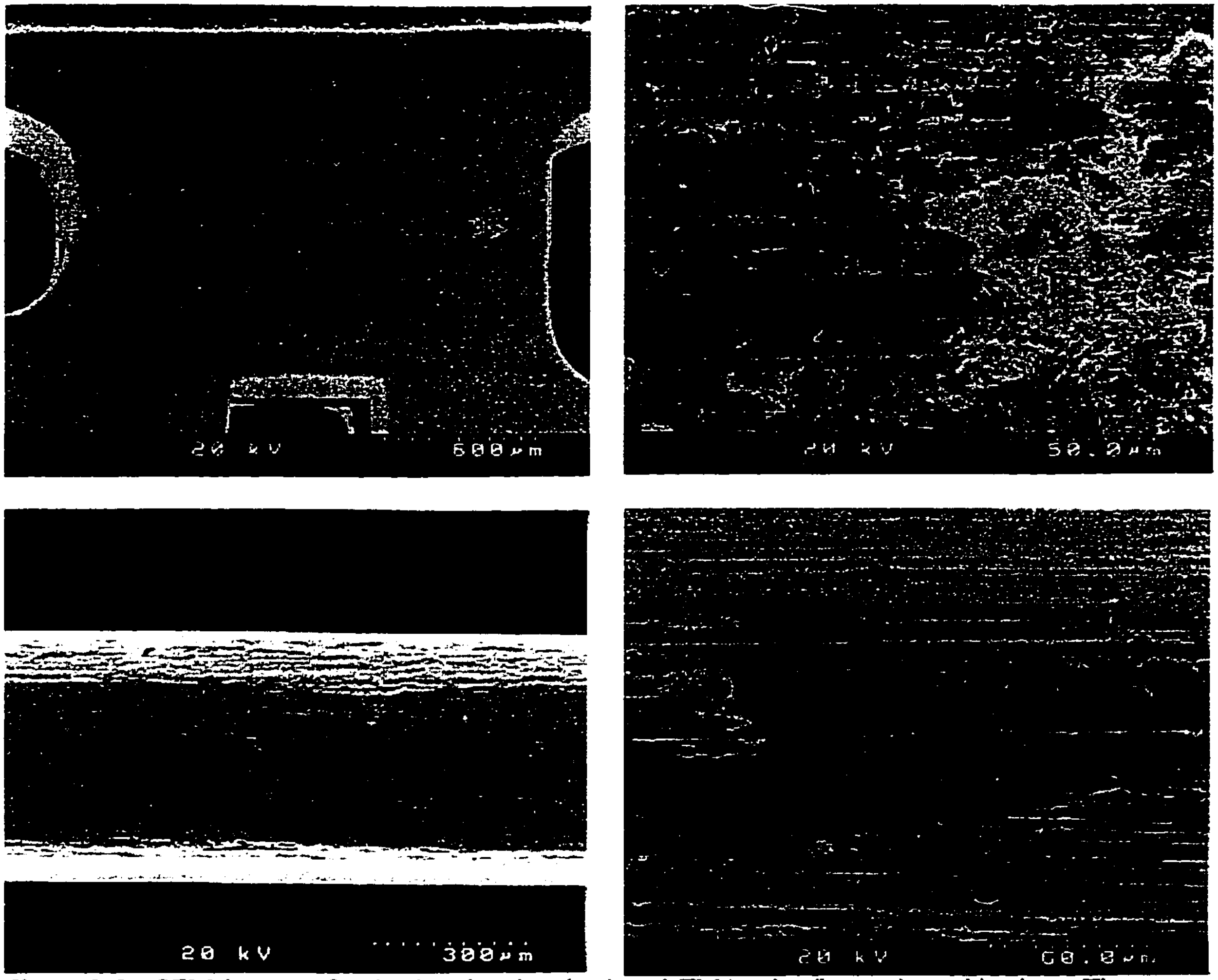


Figure 2-8. SEM images of a titanium bracket (top) and TMA wire (bottom) combination. The square areas outlined on the left images are seen under higher magnification on the right. The TMA particle (P) in addition to the wear track (W) and the plowing of the bracket surface are indicative of severe abrasion with adhesion. The TMA particle (P) and the plowing of the archwire with ribbon-like formations represent severe abrasion with adhesion.

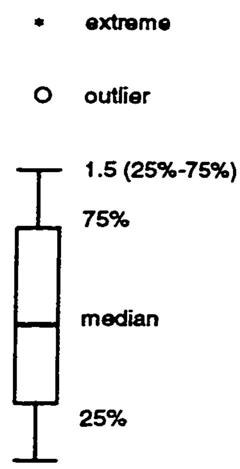


Figure 2-9. Boxplot of the coefficients of static friction of titanium and stainless steel brackets with each archwire.

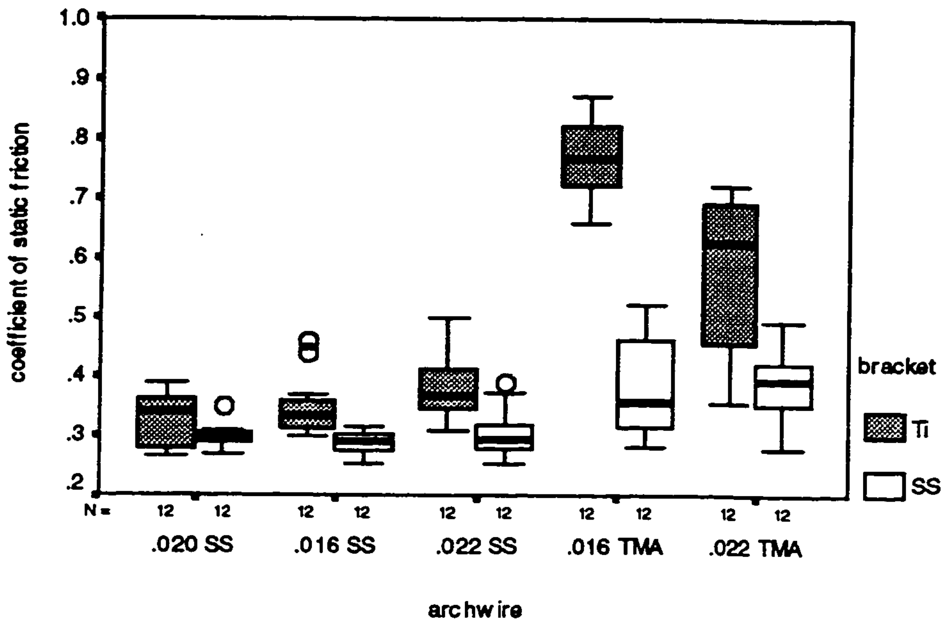


Figure 2-10. Boxplot of the coefficients of kinetic friction of titanium and stainless steel brackets with each archwire.

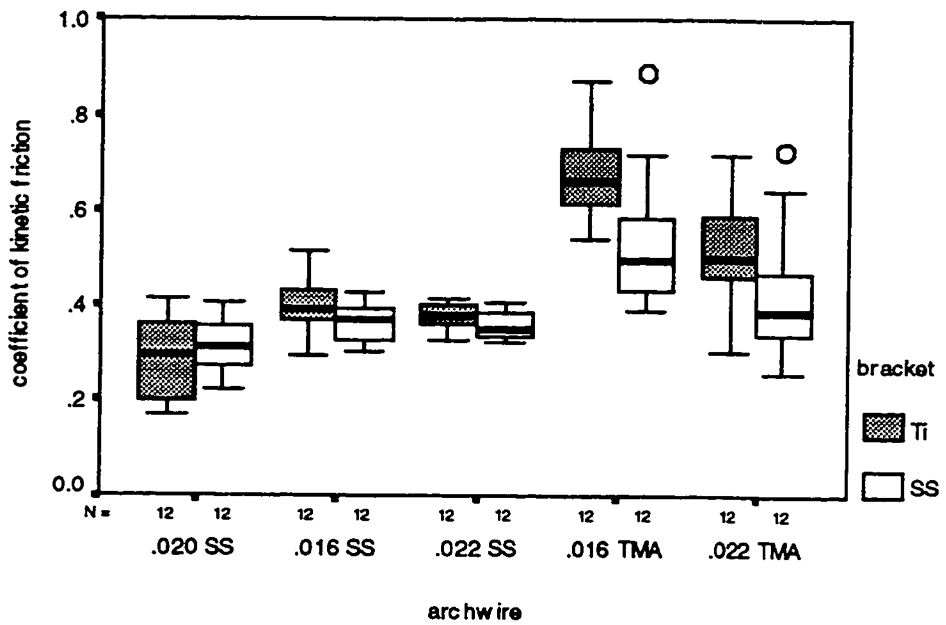


Figure 2-11. Boxplot of the coefficients of static friction of stainless steel and TMA wires for each bracket-archwire size.

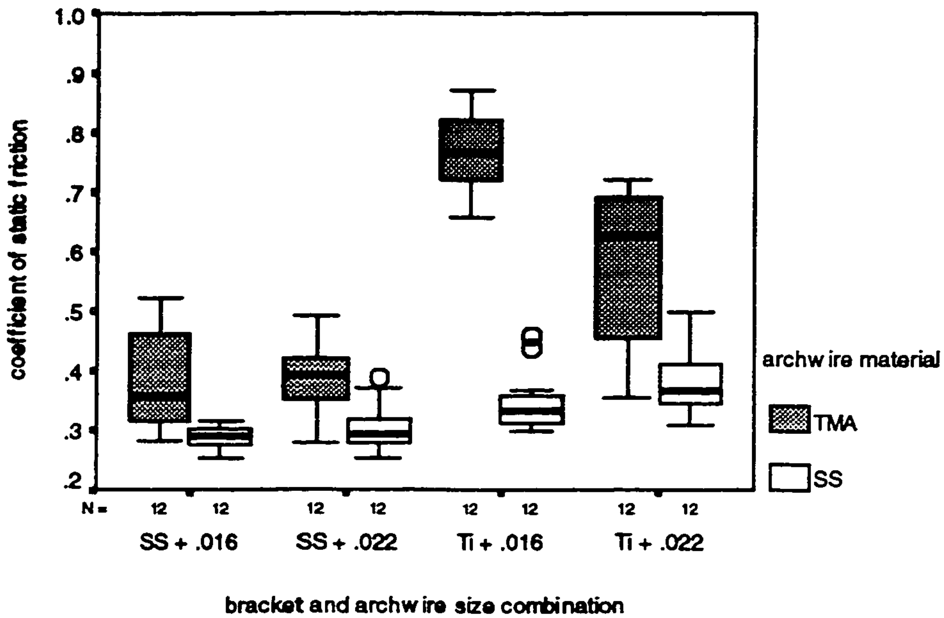


Figure 2-12. Boxplot of the coefficients of kinetic friction of stainless steel and TMA wires for each bracket-archwire size.

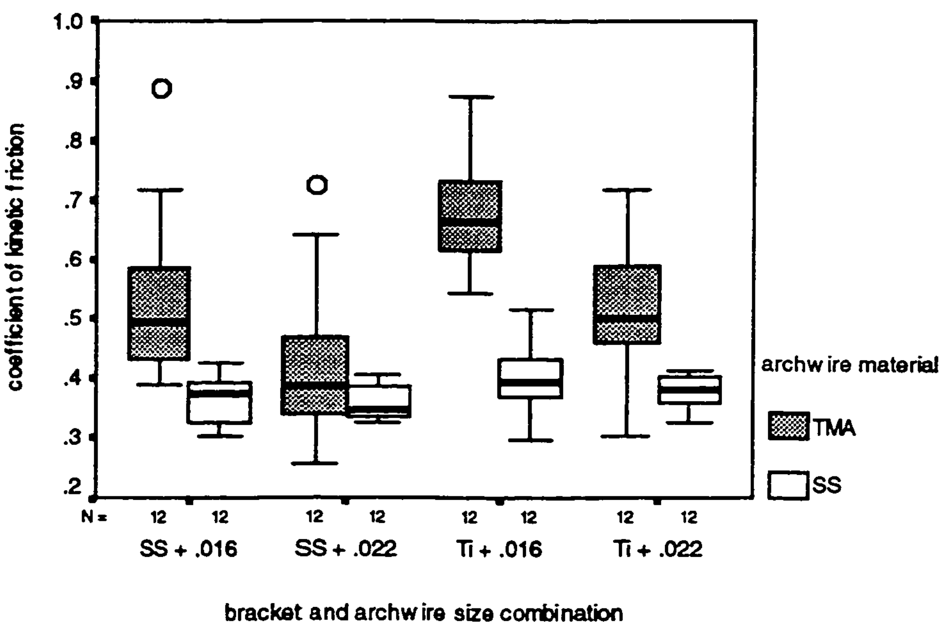


Figure 2-13. Boxplot of the coefficients of static friction

of .016" and .022" flat archwires for each bracket-wire alloy.

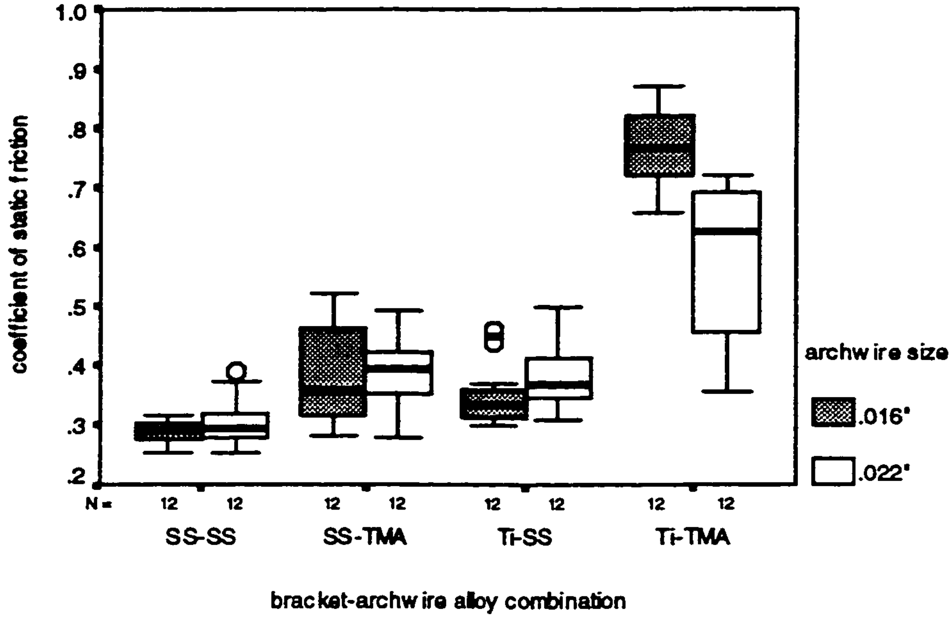


Figure 2-14. Boxplot of the coefficients of kinetic friction

of .016" and .022" flat archwires for each bracket-wire alloy.

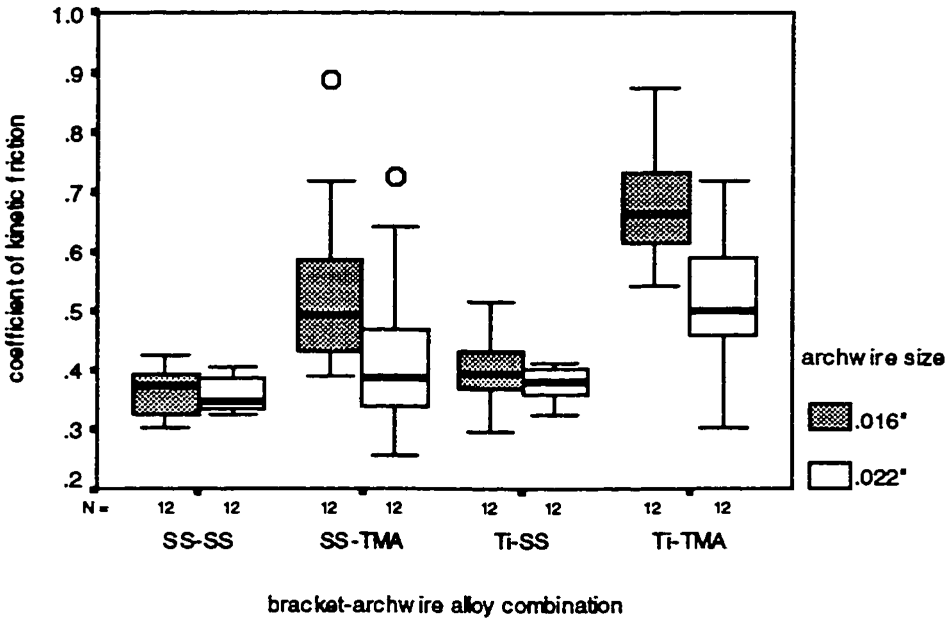


Figure 2-15. Boxplot of the coefficients of static friction of the various stainless steel wire sizes with each bracket alloy.

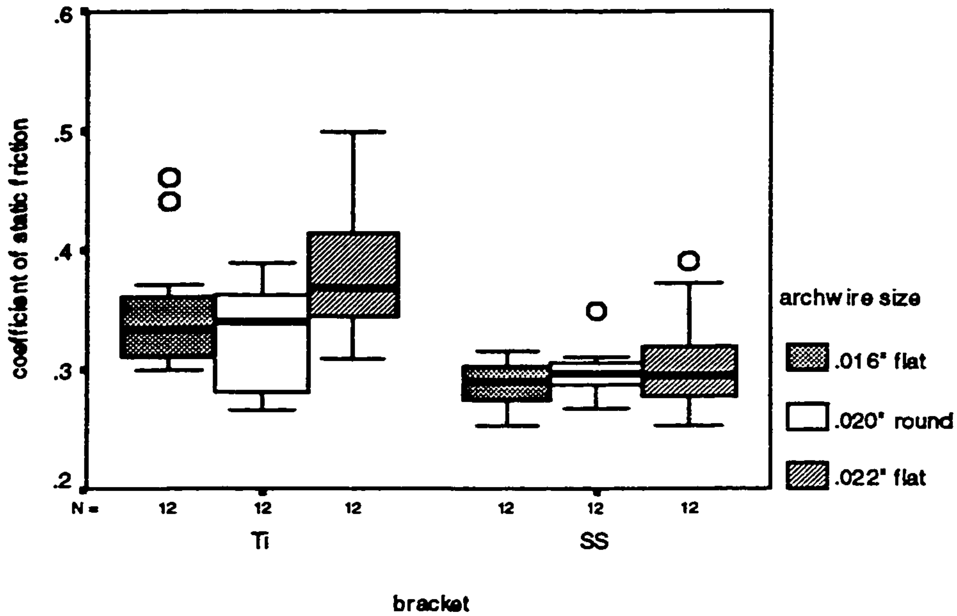
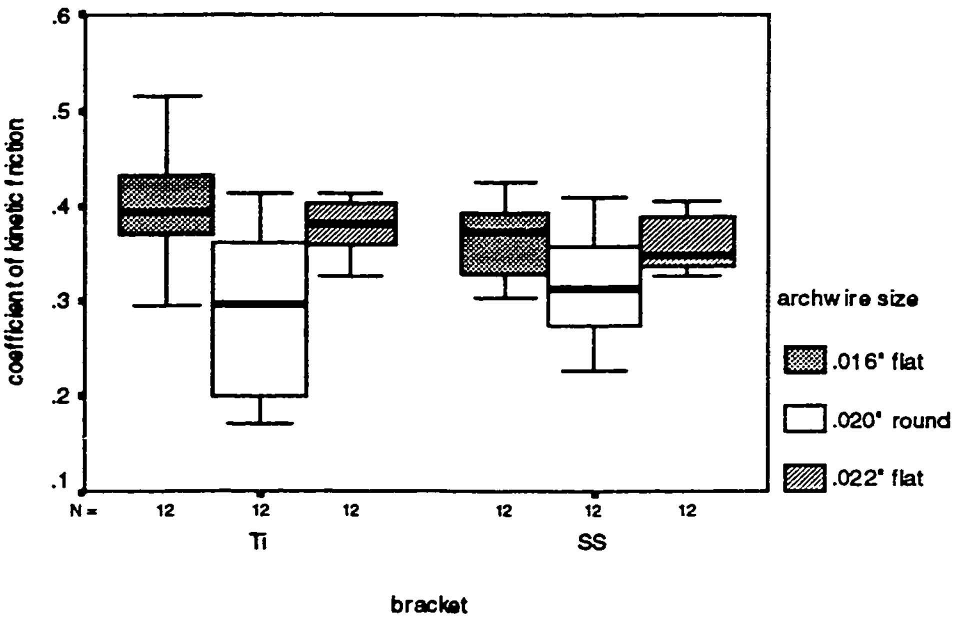
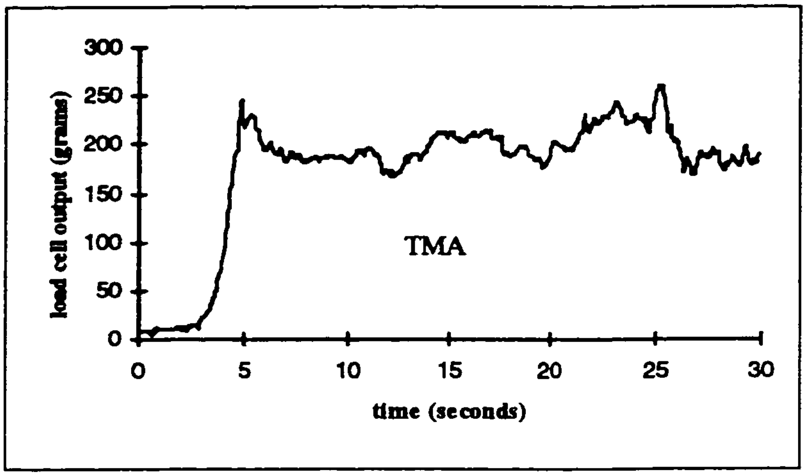


Figure 2-16. Boxplot of the coefficients of kinetic friction of the various stainless steel wire sizes with each bracket alloy.





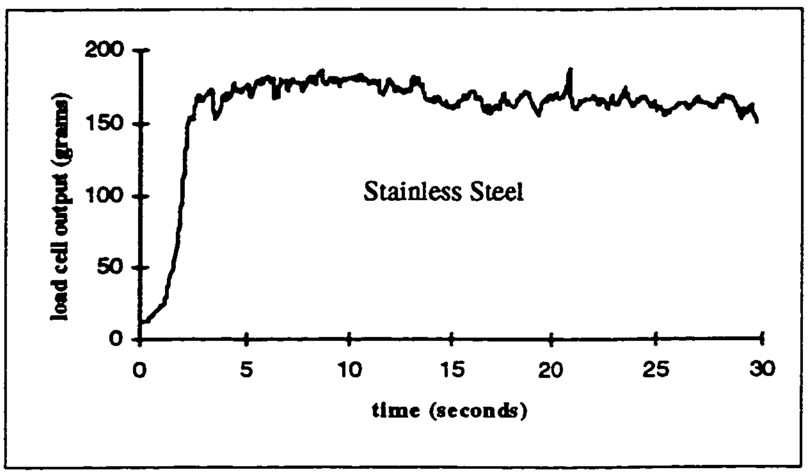


Fig 2-17. Graphical plots of friction demonstrating the greater oscillations in frictional force of a TMA wire (top) compared to a stainless steel wire (bottom).

Table 2-1. Factors influencing the friction of orthodontic appliances.

1. Bracket-Archwire Orientation and Interactions
    a) second order angulation (tip) between archwire and bracket
    b) third order angulation (torque) between archwire and bracket
    c) relative level of adjacent brackets
    d) surface interactions and wear

2. Bracket Characteristics
    a) composition
    b) width
    c) surface roughness
    d) slot size and interbracket distance
    e) surface hardness

3. Archwire Characteristics
    a) composition
    b) cross-sectional shape and size
    c) surface roughness
    d) hardness
    e) stiffness

4. Ligation Force and Method

5. The Point of Application of the Retraction Force

6. Intraoral Variables
    a) fluid media
    b) forces associated with oral functions
    c) biological resistance

Table 2-2. Experimental materials.

	Archwire and Bracket Material	Test Surface	Code
Brackets	stainless steel[α]	vertical inter-wing	SS
	titanium[δ]	lateral surface	Ti
Archwires	stainless steel[γ]		
	.020" round	round surface	.020 SS
	.016" X .022" rectangular	.016" flat surface	.016 SS
		.022" flat surface	.022 SS
	beta-titanium[♦]		
	.016" X .022" rectangular	.016" flat surface	.016 TMA
		.022" flat surface	.022 TMA

[α]Mini-V Diamond Twin (maxillary central incisor); Ormco Corp., Glendora, California
[δ]Rematitan (mandibular incisor); Dentaurum Inc., Pforzheim, Germany
[γ]Ormco Corp., Glendora, California
[♦]TMA low friction (ion-implanted); Ormco Corp., Glendora, California

Table 2-3. The recorded coefficient of friction means[θ] and standard deviations for each bracket-archwire combination.

Bracket	Archwire		Coefficient of Static Friction Mean (SD)	Coefficient of Kinetic Friction Mean (SD)
Stainless Steel	Stainless Steel	.020" Round	0.300 (0.020)	0.314 (0.057)
		.016" Flat	0.289 (0.019)	0.365 (0.040)
		.022" Flat	0.305 (0.041)	0.359 (0.028)
	TMA	.016" Flat	0.383 (0.084)	0.534 (0.145)
		.022" Flat	0.389 (0.057)	0.420 (0.143)
Titanium	Stainless Steel	.020" Round	0.326 (0.044)	0.285 (0.088)
		.016" Flat	0.348 (0.052)	0.400 (0.056)
		.022" Flat	0.387 (0.060)	0.379 (0.027)
	TMA	.016" Flat	0.767 (0.067)	0.678 (0.099)
		.022" Flat	0.583 (0.135)	0.524 (0.118)

[θ] These are derived from the values recorded by the load cell and include the friction of the Teflon-archwire interface.

Table 2-4. The coefficient of friction means and standard deviations for each Teflon-archwire combination.

Archwire		Coefficient of Static Friction Mean (SD)	Coefficient of Kinetic Friction Mean (SD)
Stainless Steel	.020" Round	0.094 (0.012)	0.057 (0.006)
	.016" Flat	0.116 (0.010)	0.063 (0.011)
	.022" Flat	0.132 (0.011)	0.068 (0.007)
TMA	.016" Flat	0.150 (0.019)	0.110 (0.017)
	.022" Flat	0.142 (0.012)	0.094 (0.014)

Table 2-5. The adjusted coefficient of friction means and standard errors for each bracket-archwire combination.

Bracket	Archwire		Coefficient of Static Friction Mean (SE)	Coefficient of Kinetic Friction Mean (SE)
Stainless Steel	Stainless Steel	.020" Round	0.206 (0.007)	0.257 (0.023)
		.016" Flat	0.173 (0.007)	0.302 (0.011)
		.022" Flat	0.173 (0.012)	0.291 (0.008)
	TMA	.016" Flat	0.233 (0.025)	0.424 (0.042)
		.022" Flat	0.247 (0.017)	0.326 (0.041)
Titanium	Stainless Steel	.020" Round	0.232 (0.013)	0.228 (0.025)
		.016" Flat	0.232 (0.015)	0.337 (0.016)
		.022" Flat	0.255 (0.017)	0.311 (0.008)
	TMA	.016" Flat	0.617 (0.020)	0.568 (0.029)
		.022" Flat	0.441 (0.039)	0.430 (0.034)

Table 2-6 Descriptions of the different bracket wear patterns.♦

Wear Category	Appearance of Test Surface on SEM
mild abrasion	• Wear scar does not exceed ½ of test surface length • Striations, grooving or scratching of test surface under 440 and 1100 times magnification
moderate abrasion	• wear scar does not exceed 1/2 of test surface length • plowing of surface with ribbon-like formations and extrusions under 440 and 1000 times magnification
severe abrasion	• wear scar exceeds 1/2 of test surface length • plowing of surface with ribbon-like formations and extrusions under 440 and 1000 times magnification
adhesion and mild abrasion	• presence of particle transfer from the wire onto the bracket surface with mild abrasion
adhesion and moderate abrasion	• presence of particle transfer from the wire onto the bracket surface with moderate abrasion
adhesion and severe abrasion	• presence of particle transfer from the wire onto the bracket surface with severe abrasion

♦ The descriptions of the severity of the wear patterns pertain to the findings of this experiment and do not represent the magnitude of wear observed in industrial engineering applications.

Table 2-7 Descriptions of the different archwire wear patterns.♦

Wear Category	Appearance of Test Surface on SEM
Mild abrasion	• striations, grooving or scratching of test surface
Severe abrasion	• plowing of surface with ribbon-like formations and extrusions
adhesion and mild abrasion	• presence of adhesive particles with mild abrasion
Adhesion and severe abrasion	• presence of adhesive particles with severe abrasion

♦ The descriptions of the severity of the wear patterns pertain to the findings of this experiment and do not represent the magnitude of wear observed in industrial engineering applications.

Table 2-8. Comparing the overall coefficients of static friction and kinetic friction of stainless steel and titanium brackets.

Friction	Bracket	Coefficient of Friction Mean (SD)	p-value
Static	SS	0.333 (0.066)	<0.0005[a]
	Ti	0.482 (0.186)	
Kinetic	SS	0.399 (0.121)	0.018[b]
	Ti	0.453 (0.159)	

[a] Kruskal Wallis One-Way Anova
[b] t-test

Table 2-9. Comparing the coefficient of static friction of stainless steel and titanium brackets with each archwire.

Archwire	Bracket	Coefficient of Friction Mean (SD)	p-value
SS .020 Round	SS	0.300 (0.020)	0.0921[a]
	Ti	0.326 (0.044)	
SS .016 Flat	SS	0.289 (0.019)	0.00015[a]
	Ti	0.348 (0.052)	
SS .022 Flat	SS	0.305 (0.041)	<0.0005[b]
	Ti	0.387 (0.060)	
TMA .016 Flat	SS	0.383 (0.084)	<0.0005[c]
	Ti	0.767 (0.067)	
TMA .022 Flat	SS	0.389 (0.057)	0.0011[a]
	Ti	0.583 (0.135)	

[a] Kruskal-Wallis One-Way Anova
[b] t-test using logarithmic transformation
[c] t-test using square root transformation

Table 2-10. Comparing the coefficient of kinetic friction of stainless steel and titanium brackets with each archwire.

Archwire	Bracket	Coefficient of Kinetic Friction Mean (SD)	p-value
SS .020 Round	SS	0.314 (0.057)	0.1715[a]
	Ti	0.285 (0.088)	
SS .016 Flat	SS	0.365 (0.040)	0.0495[b]
	Ti	0.400 (0.056)	
SS .022 Flat	SS	0.359 (0.028)	0.046[a]
	Ti	0.379 (0.027)	
TMA .016 Flat	SS	0.534 (0.145)	0.005[a]
	Ti	0.678 (0.099)	
TMA .022 Flat	SS	0.420 (0.143)	0.0325[a]
	Ti	0.524 (0.118)	

[a] t-test; [b] t-test using logarithmic transformation

Table 2-11. Comparing the overall coefficients of static friction and kinetic friction of stainless steel and TMA archwires.

Friction	Archwire	Coefficient of Friction Mean (SD)	p-value
Static	SS	0.326 (0.053)	<0.00005[a]
	TMA	0.530 (0.183)	
Kinetic	SS	0.350 (0.065)	<0.00005[a]
	TMA	0.539 (0.155)	

[a] Kruskal-Wallis One-Way Anova

Table 2-12. Comparing the coefficient of static friction of stainless steel and TMA archwires for each archwire size and bracket combination.

Bracket	Archwire	Coefficient of Friction Mean (SD)	p-value
SS	.016 SS	0.289 (0.019)	0.00075[a]
	.016 TMA	0.383 (0.084)	
	.022 SS	0.305 (0.041)	<0.0005[c]
	.022 TMA	0.389 (0.057)	
Ti	.016 SS	0.348 (0.052)	<0.0005[b]
	.016 TMA	0.767 (0.067)	
	.022 SS	0.387 (0.060)	0.00075[a]
	.022 TMA	0.583 (0.135)	

[a] Kruskal-Wallis One-Way Anova
[b] t-test using square root transformation
[c] t-test using logarithmic transformation

Table 2-13. Comparing the coefficient of kinetic friction of stainless steel and TMA archwires for each archwire size and bracket combination.

Bracket	Archwire	Coefficient of Friction Mean (SD)	p-value
SS	.016 SS	0.365 (0.040)	0.00005[a]
	.016 TMA	0.534 (0.145)	
	.022 SS	0.359 (0.028)	0.1183[a]
	.022 TMA	0.420 (0.143)	
Ti	.016 SS	0.400 (0.056)	<0.0005[b]
	.016 TMA	0.678 (0.099)	
	.022 SS	0.379 (0.027)	0.00025[a]
	.022 TMA	0.524 (0.118)	

[a] Kruskal-Wallis One-Way Anova
[b] t-test using logarithmic transformation

Table 2-14. Comparing the overall coefficients of static and kinetic friction of .022 and .016 inch flat archwire surfaces.

Friction	Archwire Size	Coefficient of Friction Mean (SD)	p-value
Static	.016	0.447 (0.199)	0.187[a]
	.022	0.416 (0.130)	
Kinetic	.016	0.494 (0.155)	0.0045[a]
	.022	0.421 (0.112)	

[a] t-test using logarithmic transformation

Table 2-15. Comparing the coefficient of static friction of .016 and .022 inch flat archwire surfaces for each bracket-archwire combination.

Bracket	Archwire	Coefficient of Friction Mean (SD)	p-value
SS	.016 SS	0.289 (0.091)	0.2917[a]
	.022 SS	0.305 (0.041)	
	.016 TMA	0.383 (0.084)	0.365[b]
	.022 TMA	0.389 (0.057)	
Ti	.016 SS	0.348 (0.052)	0.0455[c]
	.022 SS	0.387 (0.060)	
	.016 TMA	0.767 (0.067)	0.00025[a]
	.022 TMA	0.583 (0.135)	

[a] Kruskal-Wallis One-Way Anova
[b] t-test using logarithmic transformation
[c] t-test using square root transformation

Table 2-16. Comparing the coefficient of kinetic friction of .016 and .022 inch flat archwire surfaces for each archwire-bracket combination.

Bracket	Archwire	Coefficient of Friction Mean (SD)	p-value
SS	.016 SS	0.365 (0.040)	0.3475[a]
	.022 SS	0.359 (0.028)	
	.016 TMA	0.534 (0.145)	0.0325[a]
	.022 TMA	0.420 (0.142)	
Ti	.016 SS	0.400 (0.056)	0.1427[b]
	.022 SS	0.380 (0.027)	
	.016 TMA	0.678 (0.099)	0.001[a]
	.022 TMA	0.524 (0.118)	

[a] t-test
[b] Kruskal-Wallis One-Way Anova

Table 2-17. Comparing the overall coefficients of static and kinetic Friction of .016 inch flat and .020 inch round archwire surfaces.

Friction	Archwire	Coefficient of Friction Mean (SD)	p-value
Static	.016" flat	0.318 (0.049)	0.362[a]
	.020" round	0.313 (0.036)	
Kinetic	.016" flat	0.383 (0.050)	<0.0005[b]
	.020" round	0.300 (0.074)	

[a] t-test using logarithmic transformation
[b] t-test

Table 2-18. Comparing the coefficient of static friction of .016 inch flat and .020 inch round archwire surfaces for each archwire-bracket combination.

Bracket	Archwire Size	Coefficient of Friction Mean (SD)	p-value
SS	.016" flat	0.289 (0.019)	0.0865[a]
	.020" round	0.300 (0.020)	
Ti	.016" flat	0.348 (0.052)	0.133[b]
	.020" round	0.326 (0.044)	

[a] t-test
[b] t-test using logarithmic transformation

Table 2-19. Comparing the coefficient of kinetic friction of .016 inch flat and .020 inch round archwires for each archwire-bracket combination.

Bracket	Archwire	Coefficient of Friction Mean (SD)	p-value
SS	.016" flat	0.365 (0.040)	0.0095[a]
	.020" round	0.314 (0.057)	
Ti	.016" flat	0.400 (0.056)	0.0011[b]
	.020" round	0.348 (0.052)	

[a] t-test
[b] Kruskal-Wallis One-Way Anova

Table 2-20. Comparing the overall coefficients of static and kinetic friction of .020 inch round and .022 inch flat archwire surfaces.

Friction	Archwire Size	Coefficient of Friction Mean (SD)	p-value
Static	.022	0.346 (0.065)	0.0289[a]
	.020	0.313 (0.036)	
Kinetic	.022	0.369 (0.029)	0.00025[a]
	.020	0.300 (0.074)	

[a] Kruskal-Wallis One-Way Anova

Table 2-21. Comparing the coefficient of static friction of .020 inch round and .022 inch flat archwire surfaces for each archwire-bracket combination.

Bracket	Archwire Size	Coefficient of Friction Mean (SD)	p-value
SS	.022	0.305 (0.041)	0.4313[a]
	.020	0.300 (0.020)	
Ti	.022	0.387 (0.060)	0.004[b]
	.020	0.326 (0.044)	

[a] Kruskal-Wallis One-Way Anova
[b] t-test using logarithmic transformation

Table 2-22. Comparing the coefficient of kinetic friction of .020 inch round and .022 inch flat archwire Surfaces for each archwire-bracket combination.

Bracket	Archwire Size	Coefficient of Friction Mean (SD) *	p-value
SS	.022	0.359 (0.028)	0.0189[a]
	.020	0.314 (0.057)	
Ti	.022	0.379 (0.027)	0.0040[a]
	.020	0.285 (0.088)	

[a] Kruskal-Wallis One-Way Anova

Table 2-23 The coefficient of friction means for each bracket-archwire combination and the distribution of their bracket wear patterns

Bracket-Archwire Combination	Coefficient of Friction Mean (SD)		No. of Samples per Bracket Wear Pattern					
			Abrasion (Abr) Only			Adhesion and Abrasion (Abr)		
	Static	Kinetic	Mild Abr	Moderate Abr	Severe Abr	Mild Abr	Moderate Abr	Severe Abr
SS-.016 SS	0.289 (0.019)	0.365 (0.040)	8	4				
Ti-.016 SS	0.348 (0.052)	0.400 (0.056)		3	9			
SS-.016 TMA	0.383 (0.084)	0.534 (0.145)				12		
Ti-.016 TMA	0.767 (0.067)	0.678 (0.099)					4	8

Table 2-24. The coefficient of friction means for each bracket-archwire combination and the distribution of their archwire wear patterns.

Bracket-Archwire Combination	Coefficient of Friction Mean (SD)		No. of Samples per Archwire Wear Pattern		
			Abrasion (Abr) Only	Adhesion and Abrasion (Abr)	
	Static	Kinetic	Mild Abr	Mild Abr	Severe Abr
SS-.016 SS	0.289 (0.019)	0.365 (0.040)	3	9	
Ti-.016 SS	0.348 (0.052)	0.400 (0.056)		12	
SS-.016 TMA	0.383 (0.084)	0.534 (0.145)	1		11
Ti-.016 TMA	0.767 (0.067)	0.678 (0.099)			12

Table 2-25. Evaluating the associations between bracket-archwire combination, bracket alloy and archwire alloy with bracket and archwire wear.

	Wear Type	chi-square value	p-value
Bracket-Archwire Combination	Bracket	29.99220	<0.00001
	Archwire	11.55738	0.00003
Bracket Alloy	Bracket	10.32627	0.00131
Archwire Alloy	Archwire	20.80328	0.00001

Table 2-26. Coefficient of friction means and standard deviations for each bracket wear category.

Bracket Wear Pattern	Coefficient of Static Friction Mean (SD)	Coefficient of Kinetic Friction Mean (SD)
Mild abrasion	0.285 (0.020)	0.346 (0.033)
Moderate abrasion	0.305 (0.019)	0.384 (0.043)
Severe abrasion	0.358 (0.056)	0.414 (0.051)
Adhesion with mild abrasion	0.383 (0.084)	0.534 (0.145)
Adhesion with moderate abrasion	0.797 (0.060)	0.667 (0.099)
Adhesion with severe abrasion	0.752 (0.069)	0.684 (0.106)

Table 2-27. Coefficient of friction means and standard deviations for each archwire wear category.

Archwire Wear Pattern	Coefficient of Static Friction Mean (SD)	Coefficient of Kinetic Friction Mean (SD)
Mild abrasion	0.291 (0.028)	0.352 (0.046)
Adhesion with mild abrasion	0.323 (0.049)	0.390 (0.049)
Adhesion with severe abrasion	0.586 (0.207)	0.615 (0.139)

Table 2-28. Comparing the coefficient of friction means of the different bracket wear and archwire wear categories.

Wear	Coefficient of Friction	p-value
Bracket Wear	Static	<0.0001[a]
	Kinetic	<0.0001[a]
Archwire Wear	Static	<0.0001[a]
	Kinetic	<0.0001[a]

[a] Kruskal-Wallis One Way Anova

Table 2-29. Load cell reliability analysis.

Actual Mass	Measured Mean	Standard Deviation
100 g	100.0	0.19
200 g	200.1	0.18
300 g	300.0	0.24
400 g	400.2	0.23

Alpha = 0.9917

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Chapter 3

Research Paper

The Effect of Human Saliva on Friction and Stress Corrosion of Orthodontic Appliances: A Pilot Study.

3.1 Introduction

Comprehensive orthodontic treatment often involves sliding mechanics to align irregular teeth and close extraction spaces. Since this procedure involves relative motion between the brackets and archwires, frictional resistance is an inevitable phenomenon. Many researchers have studied the effects of a myriad of variables which may influence the frictional resistance of orthodontic appliances.[1-51] Although the majority of experiments have been performed under dry conditions, several researchers have investigated the friction of orthodontic appliances under fluid media in order to simulate the oral environment more closely.[1-14] Various experiments using artificial saliva and water have demonstrated that they may act as either a lubricant or an adhesive.[2-5,9,10,12-14] Studies involving human saliva have also been undertaken and the results differ from those utilizing other fluid media. While an earlier study found that human saliva did not influence friction, recent studies found that saliva increased friction for stainless steel and cobalt-chromium archwires, but decreased friction for nickel titanium and beta-titanium wires in conjunction with both stainless steel and ceramic brackets.[1,6-8,11] A recent investigation reported that artificial salivas result in much larger coefficients of friction than human saliva due to their different rheological properties and therefore they do not accurately simulate the oral environment.[51]

Experiments involving fluid media do not only offer an opportunity to study their lubricating or adhesive effects, but also their influence on the corrosion of orthodontic appliances. It has been suggested that corrosion may be the mechanism by which fluid media may increase the friction of orthodontic appliances.[10] The corrosion of orthodontic appliances has received interest due to the staining of brackets, enamel and bonding resin as well as the escalating awareness of the nickel sensitivity of some orthodontic patients.[52-55] When stainless steel interacts with oxygen a passivated layer consisting of chromium oxide and chromium hydroxide is produced on the surface. This layer provides the corrosion resistance of stainless steel. Corrosion, in turn, involves the release of metal ions from the stainless steel subsequent to the loss or breakdown of this passivated layer.[56] Studies have shown that orthodontic appliances do corrode both in clinical and in vitro situations.[54,56-64] A recent study demonstrated that the wear associated with sliding mechanics exposes fresh metallic surfaces.[65] In the presence of saliva, this offers an opportunity for stress corrosion to occur.[66] Titanium demonstrates excellent corrosion resistance and thus a newly developed pure titanium bracket (Rematitan, Dentaurum Inc., Pforzheim, Germany) has been suggested to have increased biocompatibility and corrosion resistance over currently available orthodontic brackets.[67,68]

The purpose of this study was to determine the influence of human saliva on the frictional characteristics of stainless steel brackets (Mini-V Diamond Twin, Ormco Corp., Glendora, California) and titanium brackets used in conjunction with stainless steel wires (Ormco Corp., Glendora, California) and ion-implanted beta-titanium archwires (TMA, Ormco Corp., Glendora, California). The influence of stress corrosion on the friction of these stainless steel and titanium brackets was also investigated using a "stick-slip" motion in the presence of saliva.

3.2 Materials and Method

3.2.1 The Testing Apparatus

The testing apparatus used for this investigation was modified from a previous design to accommodate the specific tests (Figures 3-1 and 3-2).[13] The brackets were bonded onto acrylic pedestals which were fastened to an adjustable stage to enable proper bracket positioning beneath the Teflon guide. This guide applied a normal load of 500 grams to the bracket-archwire interface by hanging a brass weight from a cross-beam which was connected to the Teflon guide by a vertical bearing system. An electric motor pulled the archwires across the brackets at a speed of 23 mm/minute via a pillow block, which was connected to the archwire by a thin cable. A load cell, located at the end of the pillow block, recorded the force required to pull the archwires across the brackets. The output of the strain gauge conditioner, which was connected to the load cell, was calibrated to provide an output of 1 mV/1 gram. The load cell readings were recorded by a computer for the duration of each test.

3.2.2 Preparation of the Bracket and Archwire Samples

Titanium (Ti) mandibular incisor brackets and stainless steel (SS) maxillary central incisor brackets were tested in conjunction with the .016 inch flat surface of .016 X .022 inch rectangular stainless steel (SS) and TMA archwires (Table 3-1). In order to calculate the coefficient of friction, the normal force and the frictional force between the two surfaces must be known. These are related by the equation:

$$\mu = \frac{F}{N} \quad (3\text{-}1)$$

where μ represents the coefficient of friction, F is the frictional force and N represents the normal force at the interface between the surfaces.[69] Pulling the archwire through the bracket slot would normally result in multiple surface contacts and normal forces between them, thereby increasing the complexity in calculating the coefficient of friction. Therefore, this study was designed to ensure a single surface contact interface with a constant normal force between the brackets and archwires. In order to achieve this, the vertical inter-wing surface of the stainless steel brackets[13] and the lateral surface of the titanium brackets were used in conjunction with the .016 inch flat surface of the rectangular stainless steel and TMA archwires. The laser markings on the vertical inter-wing surface of the titanium brackets precluded the use of this surface for the testing procedure. Since the slot surfaces are not preferentially treated, using different testing surfaces for the titanium and stainless steel brackets would not influence the testing results. The wings of the stainless steel brackets were removed using wire cutting pliers and any remaining metal spurs were removed with a highspeed bur so they would not interfere with the Teflon guide during the testing procedure.[13] Visual inspection ensured that the testing surface was not altered during this procedure.[13] Hooks were formed at one end of each 35 mm segment of straight archwire to provide an attachment to the motor-pulley system described below.

3.2.3 The Testing Procedure

Six independent samples of each bracket-archwire combination were tested in the presence of human saliva and in a dry environment (acting as a control). Each test involved a new bracket and archwire, which resulted in a total of 48 tests. The bracket and archwire combinations were tested in random order. Prior to testing, an adequate volume of human saliva for the entire experiment was obtained from the principal investigator, to ensure that all samples would receive a homogenous solution. Each bracket sample was bonded onto an acrylic testing base and cleaned with 95% ethanol. The archwire samples were also cleaned with 95 % ethanol and stored in a desiccator for one hour to ensure an uncontaminated testing surface. Latex gloves and cotton pliers were used to mount and align the samples to prevent contamination of the testing surfaces. For the wet samples, 0.5 ml of saliva was deposited onto the bracket testing surface with a pipette, ensuring complete wetting of the testing surface. The brass weight was attached below the adjustable stage to provide the 500 gram load at the interface. Five millimeters of archwire were pulled across the bracket surface and then held stationary for 5 minutes. Thereafter, a further 5 mm of archwire was pulled across the bracket. The load cell output for both sessions were stored in the computer and the force readings were plotted using Microsoft Excel 5.0 (Microsoft, U.S.A.). The load recorded at the initial peak represented the value of static friction. The kinetic friction was determined from the mean of the load cell output values for a duration of 10 seconds, starting 0.5 seconds after the initial static peak (Figure 3-3). Subsequently, the coefficients of friction were calculated using equation 3-1 and the mean values for the initial pulls are listed in table 3-2.

Since a Teflon guide was used to direct the wires across the brackets and apply the normal load, the force recorded by the load cell included the frictional resistance of the bracket-archwire interface and the Teflon guide-archwire interface. The results obtained, therefore, represent comparative findings, rather than absolute frictional resistances between the brackets and archwires. Teflon, which is known to have reduced friction,[70] was used so that the bracket-archwire interface would account for the majority of the frictional resistance recorded by the load cell. In order to determine the contribution of the Teflon-archwire frictional resistance to the overall force recorded by the load cell, the coefficients of friction between the Teflon guide and each archwire type were measured. This was accomplished by pulling fifteen samples of each wire type between two Teflon guides and dividing the recorded frictional force in half. The coefficient of friction means and standard deviations of the various Teflon-archwire interfaces were calculated (Table 3-3). These values were then subtracted from the corresponding bracket-archwire coefficient of friction means (Table 3-2) in order to isolate the coefficients of friction of the various bracket-archwire interfaces. These adjusted means and standard errors appear in table 3-4. The friction recordings of the individual bracket-archwire samples could not be adjusted since it was not possible to account for the variation of the Teflon–archwire interface with those values.

3.2.4 Statistical Analysis

3.2.4.a Lubrication Study

The data from the initial pulls was used to compare the frictional resistances between the dry and wet states. It would be ideal to compare the adjusted coefficient of friction means (from table 3-4) with either a t-test or a Kruskal-Wallis One-Way Anova. These adjusted values, however, did not satisfy the requirements for these tests. The t-test is a parametric test and is therefore used when the variances and standard deviations between the different groups are similar.[71] Since the standard deviations between some groups were quite different, the *p*-values would be misleading. The Kruskal-Wallis One-Way Anova (a non-parametric test) could not be performed because the adjusted frictional coefficients for the individual samples, which are normally required, could not be calculated as mentioned previously. Thus, the recorded coefficient of friction means from table 3-2 (which include the friction of the Teflon guide) were used for the statistical analyses (Tables 3-6 to 3-8, Figures 3-4 and3-5).

The means for the dry and wet states were compared for each bracket-archwire combination to determine whether they differed significantly with a p-value (one-sided) < 0.05. It was apparent from table 3-2 and the boxplots of the coefficients of friction (Figures 3-4 and 3-5) that the distribution and standard deviations between all the bracket-archwire combinations were not similar. Logarithmic and square root transformations were therefore performed in an attempt to reduce this discrepancy which would enable the use of t-tests for all comparisons. These transformations, however, were unsuccessful at achieving this for all subgroups. Consequently, either a t-test or a Kruskal-Wallis One-Way Anova was performed, depending on the ratio of the standard deviations of the groups being compared. A ratio of 1.5 was used as a guideline to differentiate similar and variable standard deviations. The Kruskal-Wallis One-Way Anova was employed when the ratio of the larger standard deviation to the smaller standard deviation was greater than 1.5. A t-test was performed when the ratio of the standard deviations was less than 1.5. A t-test using the transformed data was employed when the corresponding standard deviations led to a further reduction in the ratio.

3.2.4.b Stress Corrosion Study

The means and standard deviations of the coefficients of friction were calculated for both intervals of archwire pulls for each archwire-bracket combination. The proportionate differences between the first and second testing intervals were calculated as follows:

$$\frac{\mu_b - \mu_a}{\mu_a} \qquad (3\text{-}2)$$

where μ_a and μ_b represent the coefficients of friction for the first and second testing intervals respectively (Table 3-5). The means of the proportionate differences between the wet and dry states were then compared using a t-test or Kruskal-Wallis One-Way Anova as per the aforementioned guidelines.

3.2.5 Method Error

The samples were tested in random order to minimize the influence of experimental error on the test results. The reliability of the load cell was established by recording the load cell output when 100, 200, 300 and 400 gram brass weights were attached to the load cell and repeated 10 times. The means and standard deviations were calculated and the reliability coefficient (Cronbach's Alpha) of the repeated measures was determined to assess the internal consistency of the load cell.

3.3 Results

No significant differences ($p > 0.05$) were found between the coefficients of friction for the dry and wet states when all samples were combined collectively (Table 3-6). When each bracket-archwire combination was compared individually, it was found that saliva tended to decrease the friction of most samples (Figures 3-4 and 3-5, Tables 3-7 and 3-8). This reduction was only significant, however, for the kinetic friction of the titanium bracket-stainless steel wire couple. Saliva tended to increase the static friction of the stainless steel-TMA couple and the kinetic friction of the titanium-TMA combination. These variations, however, were insignificant ($p > 0.05$).

No significant difference ($p > 0.05$) was found in the proportionate changes recorded for the coefficients of friction between the wet and dry states when all samples were combined (Table 3-9). Similar results were found when each archwire-bracket couple was investigated individually, although a few combinations demonstrated a tendency for larger proportionate increases in saliva (Figures 3-6 and 3-7, Tables 3-10 and 3-11).

The results of the load cell reliability test are outlined in table 3-12. Because the standard deviations were similar among the different masses and the load cell demonstrated high reliability (Alpha = 0.9917), experimental error had a minimal influence on the range of variances recorded among the different bracket-archwire combinations.

3.4 Discussion

An earlier study investigated the friction and wear of orthodontic appliances in the dry state and revealed that considerable wear occurred at the bracket-archwire interface.[65] In light of these findings, this pilot study was undertaken to examine the lubricating or adhesive effects of human saliva after the initial pull and secondly, to study the possible effects of stress corrosion on a "stick-slip" pulling motion which is more characteristic of orthodontic sliding mechanics.[15-17]

Although saliva appeared to have variable influences on the coefficients of static friction, statistical analyses showed that they were insignificant, in accordance with an earlier study.[1] These findings may be attributed to the applied load forcing the saliva from between the surfaces, resulting in appreciable asperity contact between the brackets and wires before archwire movement was initiated. Under these circumstances, the rheological properties of the saliva may have been less important and this may explain the insignificant effect of saliva on static friction. This situation appears to resemble boundary lubrication.[66,69,72] The coefficients of kinetic friction were also generally unaffected by saliva, with the exception of titanium brackets combined with stainless steel archwires. These samples demonstrated decreased coefficients of kinetic friction in the presence of saliva. It appears that for this couple, the saliva provided a lubricating film between the archwires and brackets when relative movement occurred, simulating a hydrodynamic effect. It is unclear, however, why similar effects were not observed for the other bracket-archwire combinations.

This study recorded similar trends as one earlier study,[1] yet contrasted with more recent studies.[6-8,11] These recent studies employed a peristaltic pump which circulated the saliva and continually injected the fluid over the bracket-archwire assembly.[6-8,11] Under those conditions, saliva tended to increase the friction of stainless steel wires, but decrease it for titanium wires.[7,8,11] It was suggested that the saliva may have undermined the oxide layer of the stainless wires, but provided a full fluid film lubricant for the TMA wires.[8] The differing fluid dynamics between the these studies and the present one, may account for the differences recorded. The limited sample size associated with this pilot study may also be a factor. Although one may surmise that unequal salivary viscosities between the studies may have contributed to the differing results, previous research found that viscosity had no significant influence on friction.[7] Friction testing in this study was performed at 20°C, which is cooler than the ambient oral temperature of 34°C.[8] Minimal temperature differences such as this, however, would not be expected to influence friction.[69] It is important to distinguish these results from those recorded by studies which utilized artificial salivas as a lubricant, since they do not provide satisfactory simulations of in vitro environments.[51]

A previous study demonstrated that the level of friction associated with different brackets and wires was also reflected in the wear patterns exhibited by these materials.[65] Consequently, the titanium bracket – stainless steel archwire samples were investigated under the SEM to see if differences in the wear patterns between the two environments could be discerned. A classification of archwire and bracket wear, described previously, was used as a guide.[65] This preliminary investigation found wear tracks on titanium brackets in both environments (Figures 3-8 and 3-9). The bracket samples in the dry state, however, tended to exhibit severe abrasion, as indicated by the wear tracks exceeding one-half of the testing surface length. Moderate abrasion, as indicated by a shorter wear track, was generally seen in the wet state. Under higher magnification, plowing of the bracket surfaces was seen in both environments, but grooving tended to be more pronounced in the dry environment. Examining the archwires under the SEM revealed similar wear patterns for both environments, namely mild abrasion with titanium adhering to the wire surfaces (Figures 3-8 and 3-9). It appears that saliva may have decreased the asperity contacts between these brackets and archwires, resulting in decreased kinetic friction and a lesser degree of abrasive bracket wear in the wet state.

Previous research demonstrated that sliding mechanics, in the dry state, resulted in significant adhesive and abrasive wear with the exposure of fresh metallic surfaces.[65] In the oral environment, these exposed metallic surfaces could react with the saliva and undergo corrosion since their protective oxide layers were removed.[66] These corrosion products would facilitate stress corrosion at the archwire-bracket interface and subsequently increase the frictional resistance of sliding mechanics. Since tooth movement does not occur as a smooth, continuous process, the intermediate cessation in movement between the archwire and bracket may facilitate the process of stress corrosion even more by increasing the contact time between the two components. The wet pilot study entailed two pulling motions which were interrupted with a 5 minute stationary period to simulate the "stick-slip" motion occurring at the bracket-archwire interface during tooth movement. This offered a preliminary examination to assess any possible influence of stress corrosion. The proportionate changes in the coefficients of static and kinetic friction from the first to second pulling motion were calculated. A significant increase in the coefficients of friction after the second pull would lead to a positive or increased proportionate change. This phenomenon would suggest the presence of stress corrosion at the bracket-archwire interface. A negative change would result from decreased frictional coefficients for the second pull. Comparisons of the proportionate changes in the coefficients of friction, failed to detect any statistically significant differences between the dry and wet states. This suggests that stress corrosion did not alter the frictional resistances of the various bracket-archwire combinations. SEM analyses also indicated that the wear patterns were similar to the dry state and that no cratering or pitting was evident at the start of the second pull to indicate stress corrosion had occurred.[65] Although some trends may appear when assessing the frictional means, the standard deviations and variance must not be disregarded. The large standard deviations indicate tremendous variability and thus any influences of stress corrosion are difficult to ascertain. Previous research has established that orthodontic appliances do corrode in vitro when monitored over several hours to days.[56-61] While the aforementioned studies monitored corrosion by placing the orthodontic appliances in solution, this study employed a single application of saliva. It can be speculated that there was inadequate saliva at the bracket-archwire interface to initiate corrosion since the initial pulling motion may have depleted the saliva from the interface which would be required to initiate stress corrosion during the stationary period. The lack of evidence of corrosion may also suggest that 5 minutes was inadequate for the initiation of corrosion since stress corrosion testing sometimes requires several days to allow the corrodent to act.[73] Any tendency for increased frictional resistance after the 5 minute stationary period in the dry state may have resulted from settling between the brackets and archwires, during the 5 minute stationary period, which increased the junctional contact areas at the asperities. This would result in a larger true area of contact between the two surfaces and a subsequent increase in the coefficients of friction. Since the effects of stress corrosion appeared negligible, any tendency for increased friction with the second pull, in saliva, was also probably due to bracket and archwire settling during the stationary period.

Although this study used human saliva to represent the fluid composition of the oral environment, the fluid dynamics of the oral cavity were not completely simulated by this experiment. Orthodontic appliances are continually bathed in the saliva of the oral cavity and thus the single application technique may have been a limitation to this study. A continual source of saliva throughout the testing procedure may have provided a more accurate clinical situation and influenced the results recorded in this study.

3.5 Conclusions

A single application of saliva resulted in decreased kinetic friction for titanium brackets coupled with stainless steel archwires. All other coefficients of static and kinetic friction measured in this study, however, were not significantly influenced by saliva. No discernible trends were evident from the results of the stress corrosion testing. It is therefore concluded that stress corrosion did not influence the frictional coefficients when a "stick-slip" motion was simulated with a 5 minute stationary period in the presence of a single application of human saliva.

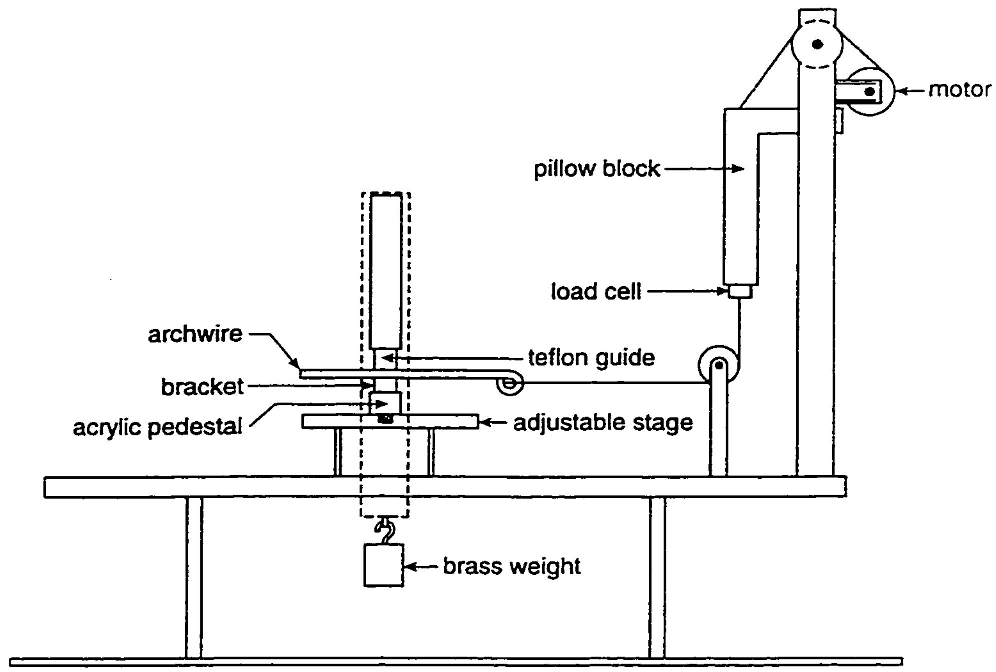


Figure 3-1. A schematic representation of the testing apparatus.

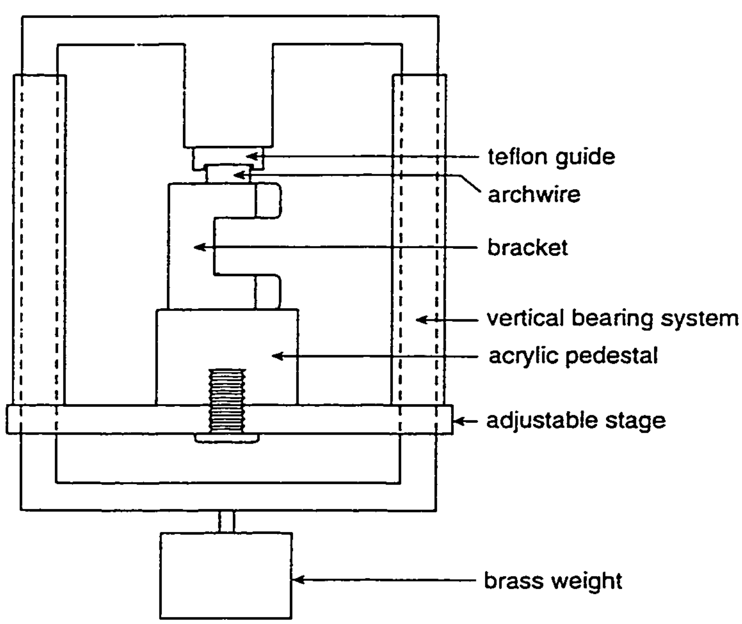


Figure 3-2. A detailed view of the bracket-archwire assembly.

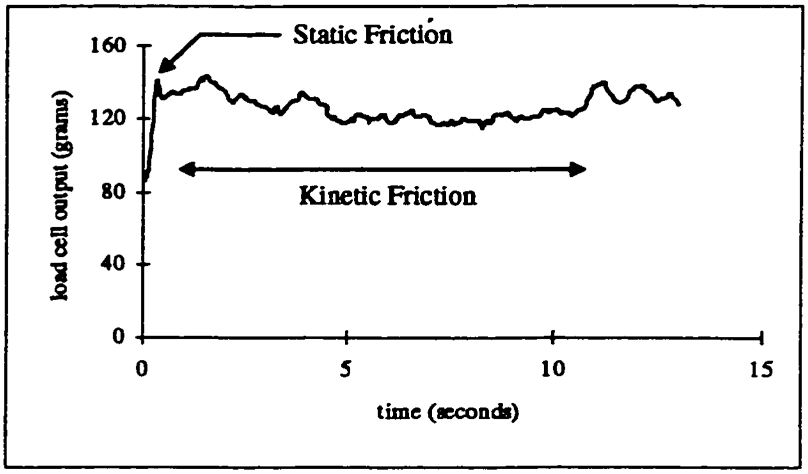


Figure 3-3. A graphical representation of the load cell output.

Figure 3-4. Boxplot of the coefficients of static friction for the dry and wet states.

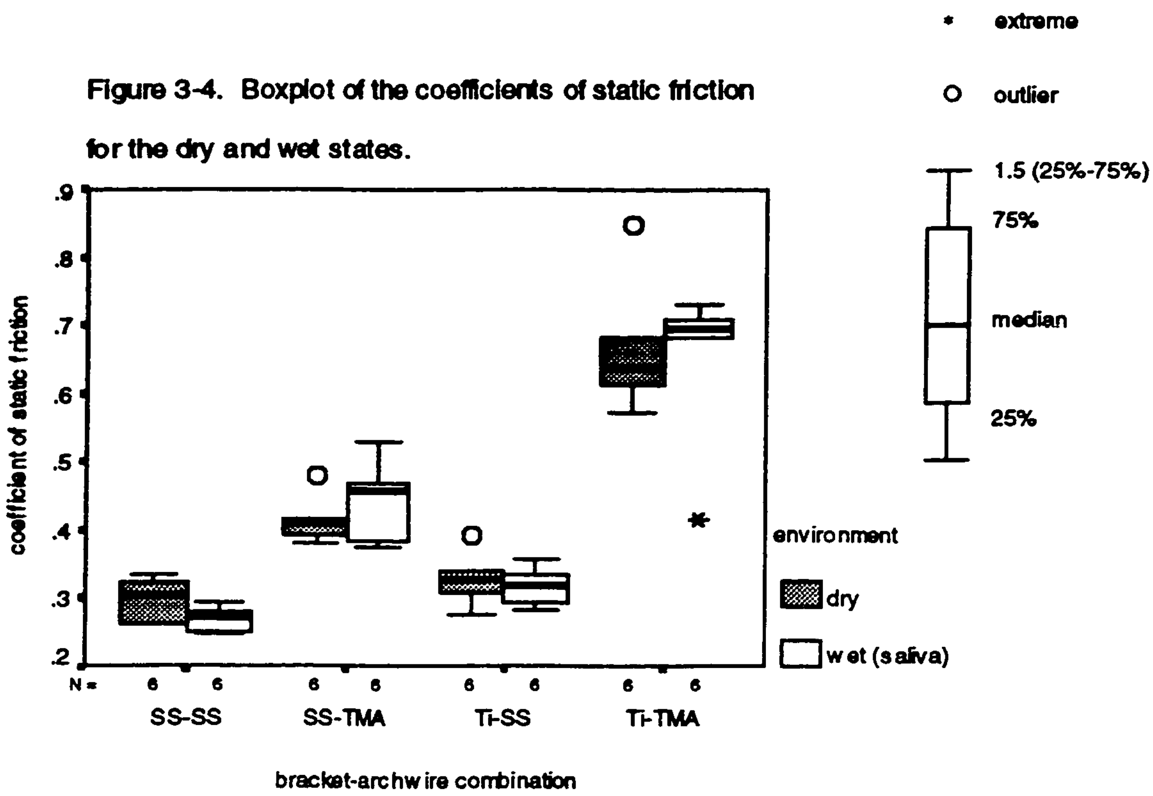


Figure 3-5. Boxplot of the coefficients of kinetic friction for the dry and wet states.

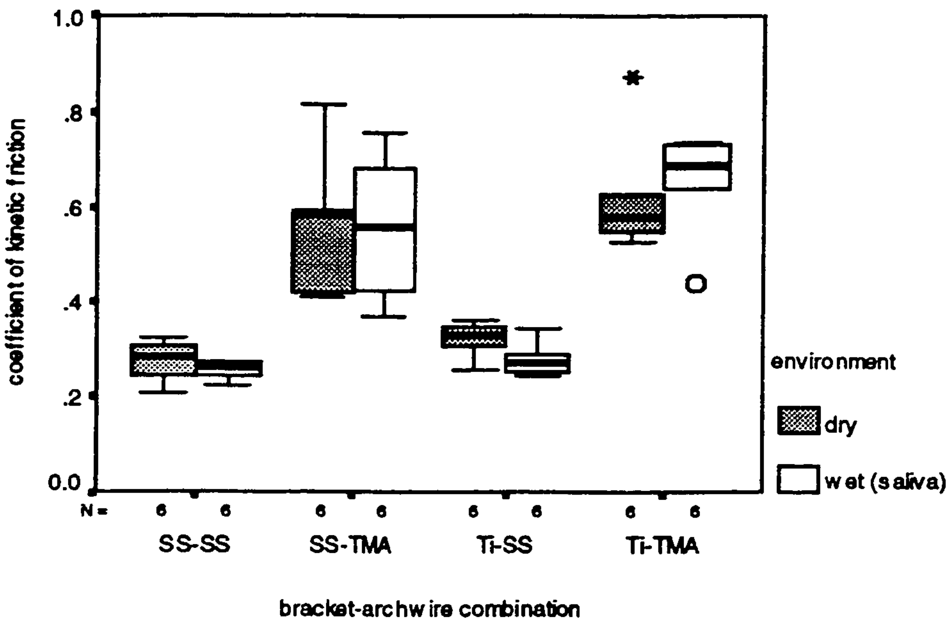


Figure 3-6. Boxplot of the proportionate changes in the coefficients of static friction for the dry and wet states.

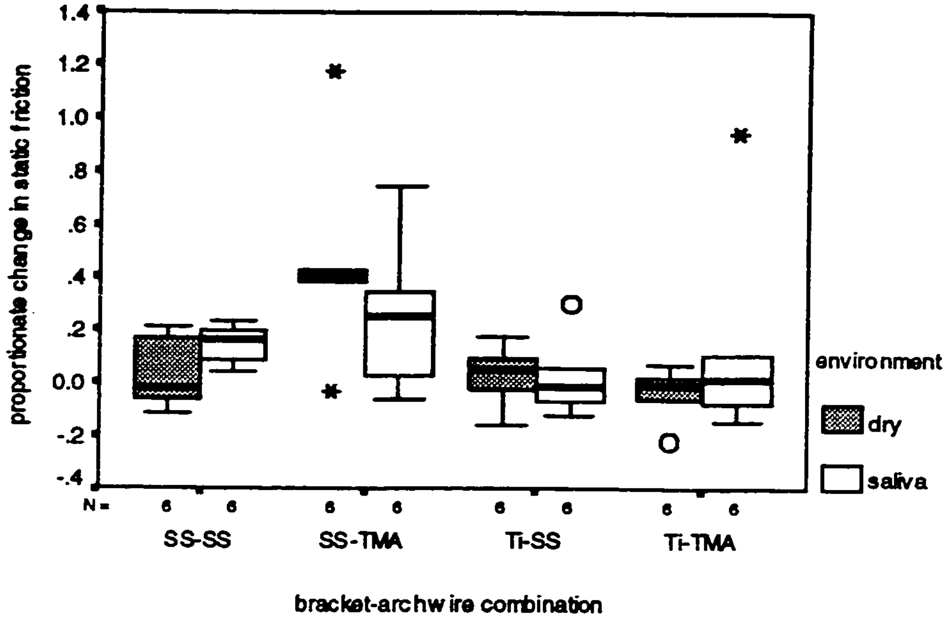
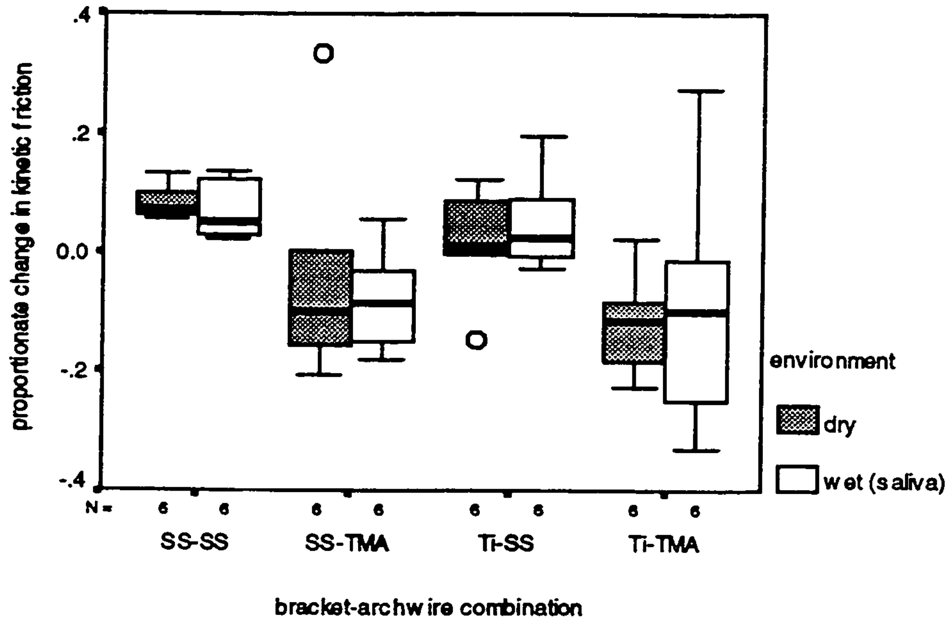


Figure 3-7. Boxplot of the proportionate changes in the coefficients of kinetic friction for the dry and wet states.



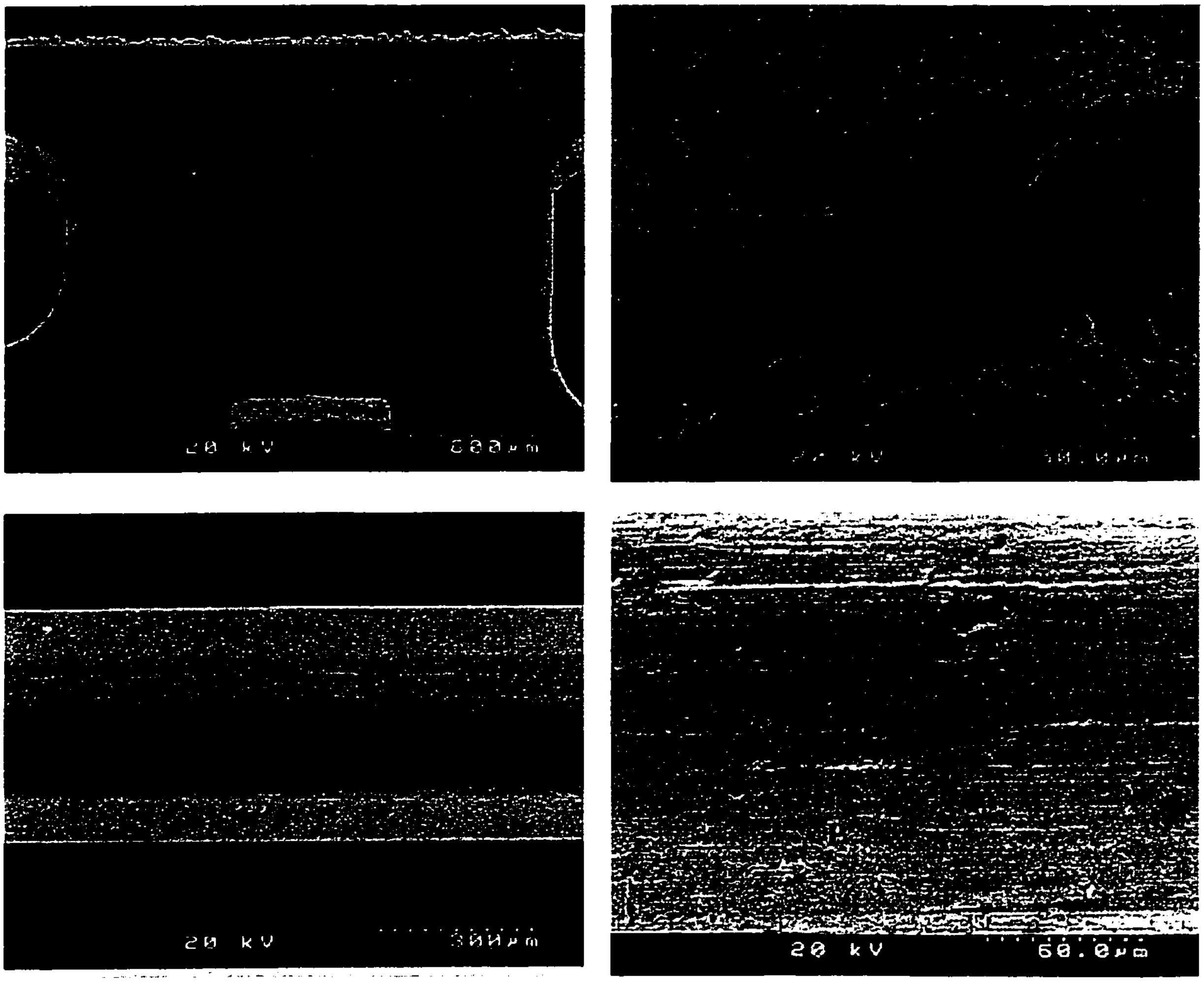


Figure 3-8. SEM images of a titanium bracket (top) and a stainless steel archwire (bottom) combination tested in the wet state. The square areas outlined on the left images are seen under higher magnification on the right. A wear track (W) with grooves (G) in the plowed region is visible on the titanium bracket. The stainless steel archwire shows titanium adhesions (P) with mild grooving and striations.

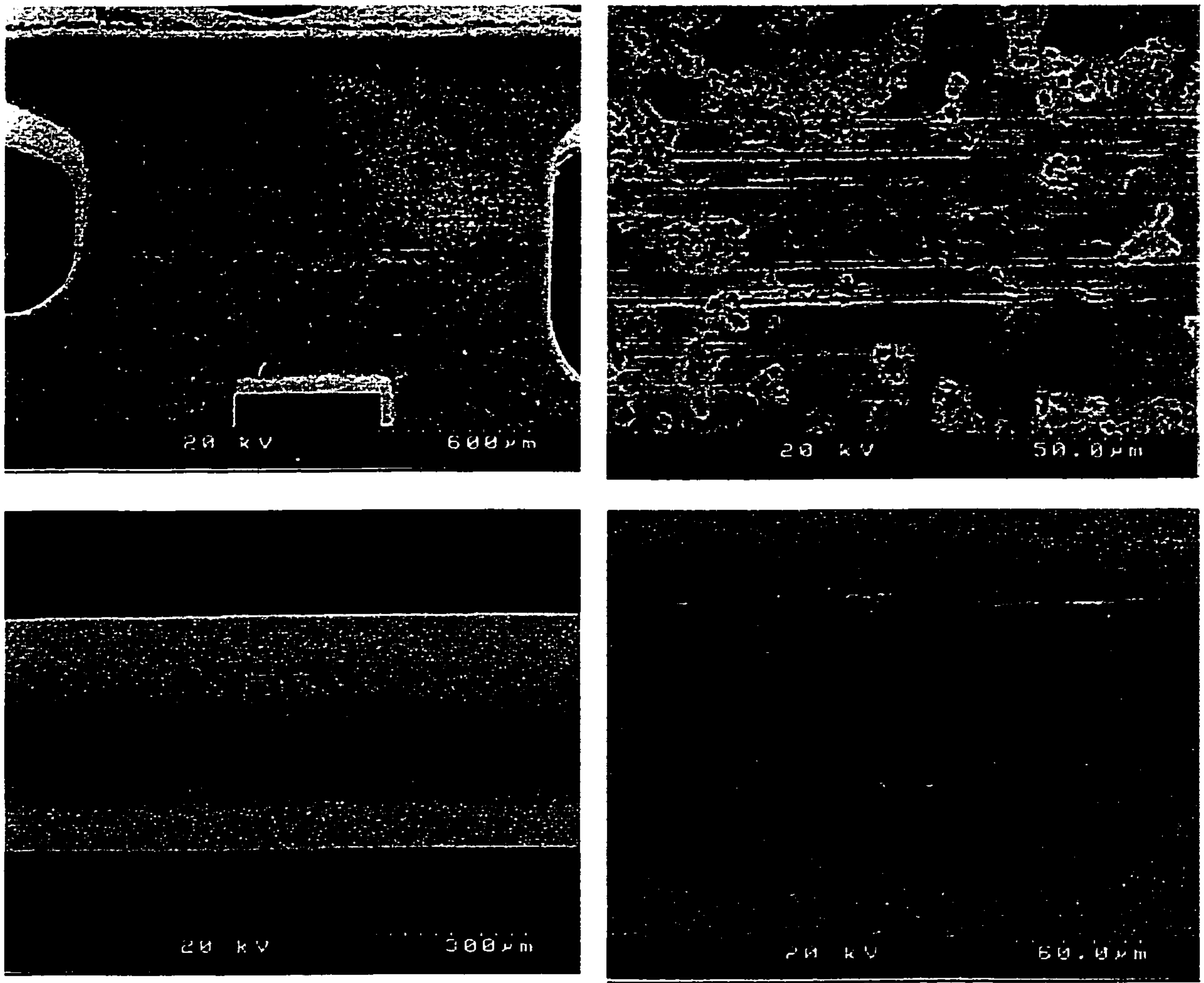


Figure 3-9. SEM images of a titanium bracket (top) and a stainless steel archwire (bottom) combination tested in the dry state. The square areas outlined on the left images are seen under higher magnification on the right. The titanium bracket demonstrates a wear track (W) with grooves (G) in the plowed region. The stainless steel archwire shows titanium adhesions (P) with mild grooving and striations.

Table 3-1. Experimental materials.

	Archwire and Bracket Material	Test Surface	Code
Brackets	stainless steel[α]	vertical inter-wing	SS
	titanium[δ]	lateral surface	Ti
Archwires	stainless steel[γ] .016" X .022" rectangular	.016" flat surface	SS .016
	beta-titanium[φ] .016" X .022" rectangular	.016" flat surface	TMA .016
Environment	dry state		
	wet state (human saliva)		

[α]Mini-V Diamond Twin (maxillary central incisor); Ormco Corp., Glendora, California
[δ]Rematitan (mandibular incisor); Dentaurum Inc., Pforzheim, Germany
[γ]Ormco Corp., Glendora, California
[φ]TMA low friction (ion-implanted); Ormco Corp., Glendora, California

Table 3-2. Recorded coefficient of friction means[θ] and standard deviations in the dry and wet (human saliva) states.

	Coefficient of Friction (Initial Pull) in the Dry State		Coefficient of Friction (Initial Pull) in the Wet State	
Bracket-Archwire Combination	Static Mean (SD)	Kinetic Mean (SD)	Static Mean (SD)	Kinetic Mean (SD)
SS-SS .016	0.297 (0.032)	0.276 (0.043)	0.269 (0.018)	0.258 (0.020)
Ti-SS .016	0.328 (0.039)	0.322 (0.037)	0.317 (0.028)	0.280 (0.037)
SS-TMA .016	0.414 (0.035)	0.566 (0.146)	0.444 (0.058)	0.558 (0.149)
Ti-TMA .016	0.665 (0.097)	0.622 (0.127)	0.655 (0.119)	0.653 (0.111)

[θ] These are derived from the values recorded by the load cell and include the friction of the Teflon-archwire interface.

Table 3-3. The coefficient of friction means and standard deviations for each Teflon-archwire combination.

	Coefficient of Friction	
Archwire	Static Mean (SD)	Kinetic Mean (SD)
SS .016	0.116 (0.010)	0.063 (0.011)
TMA .016	0.150 (0.019)	0.110 (0.017)

Table 3-4. The adjusted coefficient of friction means and standard errors for the dry and wet (human saliva) states.

	Coefficient of Friction (Initial Pull) in the Dry State		Coefficient of Friction (Initial Pull) in the Wet State	
Bracket-Archwire Combination	Static Mean (SE)	Kinetic Mean (SE)	Static Mean (SE)	Kinetic Mean (SE)
SS-SS .016	0.181 (0.013)	0.123 (0.018)	0.153 (0.008)	0.195 (0.009)
Ti-SS .016	0.212 (0.016)	0.259 (0.015)	0.201 (0.011)	0.217 (0.015)
SS-TMA .016	0.264 (0.015)	0.456 (0.060)	0.294 (0.025)	0.448 (0.061)
Ti-TMA .016	0.515 (0.040)	0.512 (0.052)	0.505 (0.049)	0.543 (0.045)

Table 3-5. The proportionate changes in the coefficients of friction[θ] between the initial and second pull for the dry and wet (human saliva) states.

	Proportionate change in the coefficient of friction between initial and second pull in the dry state		Proportionate change in the coefficient of friction between initial and second pull in the wet state	
Bracket-Archwire Combination	Static Mean (SD)	Kinetic Mean (SD)	Static Mean (SD)	Kinetic Mean (SD)
SS-SS .016	0.026 (0.132)	0.080 (0.029)	0.147 (0.072)	0.067 (0.048)
Ti-SS .016	0.031 (0.118)	0.013 (0.093)	0.022 (0.153)	0.048 (0.083)
SS-TMA .016	0.462 (0.393)	-0.038 (0.197)	0.261 (0.286)	-0.080 (0.087)
Ti-TMA .016	-0.034 (0.102)	-0.118 (0.086)	0.144 (0.406)	-0.088 (0.211)

[θ] These are derived from the values recorded by the load cell and include the friction of the Teflon-archwire interface.

Table 3-6. Comparing the overall coefficients of friction (initial pull) between the dry and wet states.

Friction	Environment	Coefficient of Friction Mean (SD)	p-value
Static	Dry	0.426 (0.157)	0.4585[a]
	Saliva	0.421 (0.165)	
Kinetic	Dry	0.447 (0.180)	0.4295[a]
	Saliva	0.437 (0.197)	

[a] t-test

Table 3-7. Comparing the coefficient of static friction (initial pull) between the wet and dry states of each bracket-archwire combination.

Bracket-Archwire Combination	Environment	Coefficient of Static Friction Mean (SD)	p-value
SS-SS .016	Dry	0.297 (0.032)	0.0547[a]
	Saliva	0.269 (0.018)	
SS-TMA .016	Dry	0.414 (0.035)	0.2609[a]
	Saliva	0.444 (0.058)	
Ti-SS .016	Dry	0.328 (0.039)	0.2935[b]
	Saliva	0.317 (0.028)	
Ti-TMA .016	Dry	0.665 (0.097)	0.439[b]
	Saliva	0.655 (0.119)	

[a] Kruskal-Wallis One-Way Anova
[b] t-test

Table 3-8. Comparing the coefficient of kinetic friction (initial pull) between the wet and dry states of each bracket-archwire combination.

Bracket-Archwire Combination	Environment	Coefficient of Kinetic Friction Mean (SD)	p-value
SS-SS .016	Dry	0.276 (0.043)	0.1486[a]
	Saliva	0.258 (0.020)	
SS-TMA .016	Dry	0.566 (0.146)	0.4595[b]
	Saliva	0.558 (0.149)	
Ti-SS .016	Dry	0.322 (0.037)	0.037[b]
	Saliva	0.280 (0.037)	
Ti-TMA .016	Dry	0.622 (0.127)	0.3295[c]
	Saliva	0.653 (0.111)	

[a] Kruskal-Wallis One-Way Anova
[b] t-test
[c] t-test using square root transformation

Table 3-9. Comparing the proportionate changes in the overall coefficients of static and kinetic friction between the wet and dry states.

Friction	Environment	Proportionate Change in the Coefficient of Friction Mean (SD)	p-value
Static	Dry	0.121 (0.289)	0.390[a]
	Saliva	0.143 (0.259)	
Kinetic	Dry	-0.0157 (0.133)	0.4745[a]
	Saliva	-0.0132 (0.136)	

[a] t-test

Table 3-10. Comparing the proportionate changes in the coefficient of static friction of each bracket-archwire combination between the dry and wet states.

Bracket-Archwire Combination	Environment	Proportionate Difference in Static Friction Mean (SD)	p-value
SS-SS .016	Dry	0.026 (0.132)	0.05465[a]
	Saliva	0.147 (0.072)	
SS-TMA .016	Dry	0.462 (0.393)	0.168[b]
	Saliva	0.261 (0.286)	
Ti-SS .016	Dry	0.031 (0.118)	0.457[b]
	Saliva	0.022 (0.153)	
Ti-TMA .016	Dry	-0.034 (0.102)	0.2609[a]
	Saliva	0.144 (0.406)	

[a] Kruskal-Wallis One-Way Anova
[b] t-test

Table 3-11. Comparing the proportionate changes in the coefficient of kinetic friction of each bracket-archwire combination between the wet and dry states.

Bracket-Archwire Combination	Environment	Proportionate Difference in Kinetic Friction Mean (SD)	p-value
SS-SS .016	Dry	0.276 (0.043)	0.1684[a]
	Saliva	0.067 (0.048)	
SS-TMA .016	Dry	-0.038 (0.197)	0.4139[a]
	Saliva	-0.080 (0.087)	
Ti-SS .016	Dry	0.013 (0.093)	0.2485[b]
	Saliva	0.048 (0.083)	
Ti-TMA .016	Dry	-0.118 (0.086)	0.500[a]
	Saliva	-0.088 (0.211)	

[a] Kruskal-Wallis One-Way Anova
[b] t-test

Table 3-12. Load cell reliability analysis.

Actual Mass	Measured Mean	Standard Deviation
100 g	100.0	0.19
200 g	200.1	0.18
300 g	300.0	0.24
400 g	400.2	0.23

Alpha = 0.9917

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Chapter 4

General Discussion and Conclusions

4.1 Discussion

Several researchers have investigated orthodontic forces in an attempt to determine the optimal force levels which result in the most efficient tooth movement. Using both clinical and histologic studies, several relationships between orthodontic force levels and tooth movement have been proposed.[1-6] Some of these theories were critically analyzed and it was found that the clinical data from these studies supported the hypothesis that the rate of tooth movement increases linearly with the applied force up to a limit. Beyond this point, an increase in force does not result in an increase in the rate of tooth movement.[7] When sliding mechanics are employed to move teeth, the applied force must overcome the frictional resistance of the appliance in order for tooth movement to occur. Since it has been suggested that the optimal force for maxillary canine retraction is between 100 and 200 grams,[7] it is imperative that the orthodontist be aware of the frictional resistance of the appliance, so that the actual residual force experienced by the tooth lies in the optimal range. A multitude of variables influence the frictional resistance of orthodontic appliances as previously outlined in table 1-2. This study investigated several of those variables: bracket alloy, archwire alloy, archwire geometry, archwire surface area, and the relationship between frictional resistance and wear patterns. The influence of human saliva on frictional resistance and the effects of stress corrosion were also evaluated in a preliminary way.

Tooth movement associated with sliding mechanics has been described as a series of short steps involving oscillating tooth tipping and uprighting, rather than a continuous, smooth gliding-like process.[8-10] Thus, both static and kinetic friction are present at the bracket-archwire interface during orthodontic tooth movement. Common observation has demonstrated that the static frictional force is generally greater than the dynamic frictional force. Thus, the same relationship exists for the coefficients of static friction (μ_s) and dynamic friction (μ_d).[11] This study, as well as previous studies, demonstrated dynamic coefficients of friction which were sometimes less than and sometimes greater than the coefficients of static friction.[12,13] It was suggested that small variations in the vertical dimensions of the wire, along the testing length, affected the interactions between the intervening components. This, in turn, altered the normal force and increased the dynamic frictional resistance.[13] Another contributing factor may be any slight curvature present in the straight archwire segments used in this study. As a slightly curved section of archwire segment was pulled through the apparatus, there may have been some binding between the archwire and the bracket edge, which increased the kinetic frictional force.

The results of this study indicated that the stainless steel brackets combined with the .016 inch flat stainless steel wire surfaces represented the lowest coefficient of static friction while titanium brackets in conjunction with stainless steel .020 inch round archwires measured the lowest kinetic friction. The highest frictional resistance was recorded with the .016 inch TMA archwire surfaces tested with titanium brackets. This combination resulted in a twofold increase in static and kinetic friction over the most efficient combinations. Further analyses showed that stainless steel brackets were associated with significantly less static and kinetic friction than titanium brackets for all archwires except the .020 inch round stainless steel wires. The lack of statistical significance with the round archwires may be attributed to the absence of edges, which may have minimized the amount of plowing otherwise noted with the .016 inch flat surface of .016 X .022 archwires under the SEM. The largest difference between the frictional coefficients of titanium and stainless steel brackets was noted with TMA archwires. Titanium brackets had twice as much friction as stainless steel brackets when tested with the .016 inch flat TMA surfaces.

With respect to the archwire alloys, stainless steel archwires had significantly lower coefficients of static friction and kinetic friction in agreement with several previous studies.[9,12-24] One exception, however, was observed with the .022 inch flat wire surface in conjunction with stainless steel brackets. The high variability of the TMA wires may account for the lack of a significant difference between the kinetic friction means of the two alloys. While some previous investigators have attributed the increased friction of TMA to its increased surface roughness relative to stainless steel archwires, not all studies found a clear correlation between friction and surface roughness.[12,16,20,23,25] This study did not investigate the effect of surface roughness. Under the SEM, however, TMA wires did appear to have a rougher and more porous surface than stainless steel wires.

An overall aim of this study was to investigate the tribological properties of orthodontic appliances. In particular, the association between wear, friction and the various bracket and archwire materials was of interest. This was achieved by using the SEM to observe and compare the wear patterns of the combinations involving the stainless steel and titanium brackets in conjunction with the .016 inch flat surface of both stainless steel and TMA archwires. The posttest scanning electron micrographs of the brackets and archwires were examined and then assigned, in a blinded fashion, to one of the various wear patterns outlined in tables 2-6 and 2-7. Both categorization techniques demonstrated high reliability. The distribution patterns of the wear counts for the four bracket-archwire combinations, outlined in tables 2-23 and 2-24, display how the bracket and archwire wear patterns varied significantly with the various bracket-archwire combinations. The stainless steel bracket - stainless steel archwire combination recorded the lowest frictional means and was associated with mild and moderate abrasive bracket wear with the majority of the wires demonstrating mild abrasion with adhesion. The titanium bracket - TMA wire couple demonstrated the highest frictional values and was associated with moderate to severe bracket abrasion with TMA adhesions, while the archwires demonstrated severe abrasion with adhesion.

The coefficients of friction of the different wear patterns were also significantly different ($p < 0.05$), indicating an association between wear and friction. A general pattern between increasing bracket abrasion and increasing coefficients of friction is apparent in table 2-26 with the exception of moderate abrasion and severe abrasion in conjunction with adhesion. The length of the wear track on the bracket surface distinguished these two patterns, which were exhibited by titanium brackets tested with TMA wires exclusively. The increased static friction of moderate abrasion relative to severe abrasion may suggest that the brackets and archwires were not perfectly parallel thereby resulting in one of the bracket edges being more prominent. This may have simulated archwire to bracket binding which has been implicated as an important contributor to friction.[10,26]

The general trend of increased friction of the titanium brackets is also reflected in the increased coefficient of friction means of the wear patterns exhibited by these brackets. When both brackets were tested with TMA wires, posttest SEM analyses identified particles on both bracket surfaces. Energy dispersive x-ray analysis (EDX) revealed that these particles contained titanium, molybdenum, zirconium and tin, all of which are constituents of TMA wires. Thus, it was clear that both brackets demonstrated adhesive wear when tested with TMA archwires. The abrasive component of the wear pattern with titanium, however, was generally more severe than stainless steel. The prominent abrasive wear tracks and increased coefficients of friction of titanium brackets suggest that the titanium brackets are softer than the stainless steel brackets since friction and hardness are inversely related.[27] The oxide layer on the surface of metals provides a protective film and prevents adhesion as long as it is not penetrated.[28] Titanium has been described as having a relatively impervious and protective oxide layer.[29] This experiment revealed that the oxide layer of the titanium brackets was penetrated as demonstrated by the adhesion between these brackets and both archwires. Thus, the oxide layer does not appear to provide a good physical barrier for improved orthodontic sliding mechanics.

While both stainless steel and TMA archwires tended to demonstrate adhesive wear, the abrasive wear observed on the TMA archwires was generally more severe than that observed on the stainless steel wires. Furthermore, the archwire wear group representing the majority of TMA wires (adhesion and severe abrasion) had a two fold increase in friction over the archwire wear patterns demonstrated by the stainless steel wires (mild abrasion without adhesion and mild abrasion with adhesion). This explains the increased friction associated with TMA wires. Energy dispersive x-ray analysis confirmed that the adhesive particles present on the TMA archwires were from the archwire itself and not from the titanium or stainless steel brackets. This suggests that when cold welding occurred between the brackets and TMA archwires, the adhesive junction was stronger than the internal strength of the TMA wire.[28] Thus, shearing occurred within the TMA and wear particles from the wire were produced resulting in a three-body abrasive wear system. With further archwire sliding, these particles readhered to the TMA surface.

When stainless steel wires were slid across titanium brackets, titanium adhesions were detected on the stainless steel wires. This suggests that the cohesive forces within the titanium were inferior to the adhesive strength of the stainless steel-titanium junctions. Since this is opposite to the material transfer seen with TMA wires, this confirms a previous finding that TMA wires are softer than stainless steel wires.[21] The difference in hardness between these two wires is a contributing factor to the increased coefficients of friction of TMA wires.[27] The friction plots of the TMA wires appeared to demonstrate larger oscillations in frictional force than those of the stainless steel wires. These fluctuations in force may indicate the forming and breaking of adhesive junctions leading to the increased severity of wear and the higher coefficients of friction associated with TMA wires.[12]

When stainless steel brackets were tested with stainless steel archwires, particles were detected on the wire surfaces but not on the bracket surfaces. Since the brackets and wires are of the same material, EDX was not able to determine the origin of these particles. SEM analyses of the bracket and archwire surfaces did not reveal any pitting which would indicate the origin of these particles. One reason for the absence of pitting may be that they were originally present and subsequently filled in with the abrasive wear process of sliding mechanics. These particles may also be the result of adhesions occurring at localized areas of internal weaknesses within the wire resulting from manufacturing defects. If the strength of the adhesive junction exceeded the cohesive strength within the defect, shearing occurred along the weakened internal planes of the wire and resulted in particle formation.

This study also investigated the second law of friction which states that friction is independent of the apparent area of contact.[30,31] Although stainless steel wires were generally in accordance with this law, exceptions were noted with TMA wires. The significantly larger coefficients of friction of the .016 inch surface TMA archwires relative to the .022 inch TMA surfaces may have resulted from slight archwire tilting during the testing, resulting in a prominent edge and increased wear. This edge effect may have been further exacerbated by the increased severity of wear that was observed with TMA wires. The effect of archwire size on friction has been studied extensively and it was generally found that frictional resistance generally increased with an increase in archwire dimension.[8-10,14,16,17,22,24,32-41] Although these findings appear contradictory to the findings of this study or to the second law of friction, some explanations are possible. The other studies pulled the wires through the slot and thus the normal forces between the various slot walls and the wire surfaces were difficult to control. This resulted in variable normal forces, which in turn influenced the frictional forces recorded by the other investigations. Furthermore, the increased friction with larger wires may have been attributed to the use of elastomeric ligatures in some experiments. These ligatures were under more tension with larger archwires, resulting in increased normal forces and thus increased friction.[17] Some researchers found that larger wires did not always lead to increased friction and suggested that it may be due to the larger wires occupying the slot more and decreasing the binding angle.[8,24,35,42]

The orthodontic literature revealed that round wires generally produced less friction than rectangular wires, but some exceptions were noted.[10,14,23,24,32,36-38,41-43] For example, 0.016 inch round and .016 x 0.022 inch rectangular stainless steel wires used in conjunction with 0.0185 inch slot brackets had similar frictional levels.[9] This emphasized the importance of considering the occlusogingival dimension when comparing round and rectangular archwires. Furthermore, binding is another factor that must be considered when testing involved passing the archwire through the slot since larger and stiffer wires would result in larger normal forces at the bracket-archwire interface at binding angulations.[10,44] This concept was demonstrated when .020 round archwires produced more friction at binding angulations than rectangular archwires with smaller occlusogingival dimensions.[10,37] In order to eliminate the possible influence of binding, the design of this study entailed single surface interfaces. There was a tendency for the flat stainless steel archwire surfaces to have similar static friction coefficients as the .020 inch round stainless steel archwires. The coefficients of kinetic friction of the flat surfaces, however, were significantly greater than the round wires. This general trend being limited to the kinetic friction suggests that during the sliding process there may have been some archwire tilting. This corresponded to one edge being more prominent and possibly increased the plowing component of wear which significantly increased the kinetic friction of the rectangular wires.

The initial section of this thesis investigated the friction and wear of orthodontic appliances in the dry state and revealed that considerable wear occurred at the bracket-archwire interface. In light of these findings, a pilot study was undertaken which tested titanium and stainless steel brackets with the .016 inch flat surface of stainless steel and

TMA archwires in the presence of saliva. The purpose was twofold: to examine the lubricating or adhesive effects of human saliva after the initial pull and secondly, to study the possible effects of stress corrosion on a "stick-slip" pulling motion which is more characteristic of orthodontic sliding mechanics.[8,9,10] Although the previous section contained a detailed investigation of the dry state, the second section also included tests in the dry state to act as a control, particularly for the "stick-slip" motion.

Although saliva appeared to have variable influences on the coefficients of static friction, statistical analyses showed that they were insignificant. These results are similar to those recorded by Andreasen and Quevedo, (1970).[32] These findings may be attributed to the applied load forcing the saliva from between the surfaces, resulting in appreciable asperity contact between the brackets and wires before archwire movement was initiated. Under these circumstances, the rheological properties of the saliva may have been less important and this may explain the insignificant effect of saliva on static friction. This situation appears to resemble boundary lubrication.[30,31,46] The coefficients of kinetic friction were also generally unaffected by saliva, with the exception of titanium brackets combined with stainless steel archwires. These samples demonstrated decreased coefficients of kinetic friction in the presence of saliva. It appears that for this couple, the saliva provided a lubricating film between the archwires and brackets when relative movement occurred, simulating a hydrodynamic effect. It is unclear, however, why similar effects were not observed for the other bracket-archwire combinations.

This study recorded similar trends as one earlier study,[32] yet contrasted with more recent studies.[18,19,21,45] These recent studies employed a peristaltic pump which circulated the saliva and continually injected the fluid over the bracket-archwire assembly.[18,19,21,45]

Under those conditions, saliva tended to increase the friction of stainless steel wires, but decrease it for titanium wires.[19,21,45] It was suggested that the saliva may have undermined the oxide layer of the stainless wires, but provided a full fluid film lubricant for the TMA wires.[19] The differing fluid dynamics between the these studies and the present one, may account for the differences recorded. The limited sample size associated with this pilot study may also be a factor. Although one may surmise that unequal salivary viscosities between the studies may have contributed to the differing results, previous research found that viscosity had no significant influence on friction.[45] Friction testing in this study was performed at 20°C, which is cooler than the ambient oral temperature of 34°C.[19] Minimal temperature differences such as this, however, would not be expected to influence friction.[31] It is important to distinguish these results from those recorded by studies which utilized artificial salivas as a lubricant, since they do not provide satisfactory simulations of in vitro environments.[47]

The first section of this thesis demonstrated that the level of friction associated with different bracket-archwire combinations was also reflected in the wear patterns exhibited by these materials. Consequently, the titanium bracket – stainless steel archwire samples were investigated under the SEM to see if differences in the wear patterns between the two environments could be discerned. The classification of archwire and bracket wear derived in the first section was used as a guide. This preliminary investigation found wear tracks on titanium brackets in both environments (Figures 3-8 and 3-9). The bracket samples in the dry state, however, tended to exhibit severe abrasion, as indicated by the wear tracks exceeding one-half of the testing surface length. Moderate abrasion, as indicated by a shorter wear track, was generally seen in the wet state. Under higher magnification, plowing of the bracket surface was seen in both environments, but grooving tended to be more pronounced in the dry environment. Examining the archwires under the SEM revealed similar wear patterns for both environments, namely mild abrasion with titanium adhering to the wire surfaces (Figures 3-8 and 3-9). It appears that saliva may have decreased the asperity contacts between these brackets and archwires, resulting in decreased kinetic friction and a lesser degree of abrasive bracket wear in the wet state.

The friction and wear study in the dry state demonstrated that sliding mechanics resulted in significant adhesive and abrasive wear. Consequently, fresh metallic surfaces were exposed. In the oral environment, these exposed metallic surfaces could react with the saliva and undergo corrosion since their protective oxide layers were removed.[46] These corrosion products would facilitate stress corrosion at the archwire-bracket interface and subsequently increase the frictional resistance of sliding mechanics. Since tooth movement does not occur as a smooth, continuous process, the intermediate cessation in movement between the archwire and bracket may facilitate the process of stress corrosion even more by increasing the contact time between the two components. The wet pilot study offered a preliminary examination to assess any possible influence of stress corrosion. The proportionate changes in the coefficients of static and kinetic friction from the first to second pulling motion were calculated. A significant increase in the coefficients of friction after the second pull would lead to a positive or increased proportionate change. This phenomenon would suggest the presence of stress corrosion at the bracket-archwire interface. A negative change would result from decreased frictional coefficients for the second pull. The proportionate changes in the wet and dry states were compared to determine whether similar trends would be found in the dry state. Similar trends between the wet and dry state would negate the influence of stress corrosion since the dry state did not provide a suitable environment for corrosion. Comparisons of the proportionate changes in the coefficients of friction failed to detect any statistically significant differences between the dry and wet states. This suggests that stress corrosion did not significantly alter the frictional resistances of the various bracket-archwire combinations of this experiment. SEM analyses also indicated that the wear patterns were similar to the dry state and that no cratering or pitting was evident at the start of the second pull to indicate stress corrosion. Although some trends may appear when assessing the frictional means, the standard deviations and variance must not be disregarded. The large standard deviations indicated tremendous variability and thus any influences of stress corrosion are difficult to ascertain. Previous research has established that orthodontic appliances do corrode under both clinical and in vitro situations.[48-58] While the in vitro investigations monitored corrosion by placing the orthodontic appliances in solution for several days, this study employed a single application of saliva. It can be speculated that there was inadequate saliva at the bracket-archwire interface to initiate corrosion since the initial pulling motion may have depleted the saliva from the interface which would be required to initiate stress corrosion during the stationary period. The lack of evidence of corrosion may also suggest that 5 minutes was inadequate for the initiation of corrosion since stress corrosion testing sometimes requires several days to allow the corrodent to act.[59] Any tendency for increased frictional resistance after the 5 minute stationary period in the dry state may have resulted from settling between the brackets and archwires, during the 5 minute stationary period, which increased the junctional contact areas at the asperities. This would result in a larger true area of contact between the two surfaces and a subsequent increase in the coefficients of friction. Since the effects of stress corrosion appeared negligible, any tendency for increased friction with the second pull, in saliva, was also probably due to bracket and archwire settling during the stationary period.

The engineering field has employed various methods to measure wear. Measuring weight changes has been regarded as one of the simplest ways of detecting wear.[31] This study attempted to use this method by weighing the wire samples before and after testing to analyze weight changes associated with the wear of sliding mechanics. The wire samples were cleaned with 95 % ethanol and then desiccated, prior to the obtaining their weight, to ensure that no contaminants on the wire would obscure the measurements. Results from this procedure, however, indicated that the precision of the analytical scale used was inadequate for detecting weight changes. If the changes in weight could be measured, it would be expected that TMA wires would record weight losses since particles from these wires were transferred to the surfaces of both the titanium and stainless steel brackets. The stainless steel wires tested with titanium brackets would be expected to record a gain in weight since cold welding resulted in titanium particles adhering to the wire. The origin of the stainless steel particles was not established as previously described. Detectable weight changes of the wires may have helped establish the nature of the adhesive process observed between stainless steel brackets and archwires.

4.2 Clinical Implications

The findings from this experiment reveal that stainless steel brackets with stainless steel archwires provided a more efficient orthodontic appliance than the other bracket-archwire combinations tested. The results further suggest the use of round wires for sliding mechanics, since the coefficients of kinetic friction of the stainless steel rectangular wires were significantly larger. Thus, the clinical and anecdotal findings of reduced friction with round wires appears valid. This may be due to the lack of an edge effect with round wires. This is particularly important if sliding mechanics is attempted when the adjacent bracketed teeth have large differences in torque. This would most likely lead to edge effects in the brackets and decrease the efficiency orthodontic tooth movement. Although the coefficients of friction of the stainless steel brackets were less than titanium brackets, it was not significant when tested with .020 inch round stainless steel wires. This finding may suggest that titanium brackets would provide efficient sliding mechanics with .020 inch round stainless wires. TMA wires do not appear suitable for sliding mechanics due to their large coefficients of friction, particularly with titanium brackets. Since friction and material hardness are reciprocally related, brackets and wires manufactured from soft metals should be avoided.

Anchorage, as it pertains to orthodontics, is defined as the resistance to unwanted tooth movement.[44] Controlling anchorage is a crucial aspect of orthodontic treatment so that tooth movement can be controlled. Several methods have been suggested to increase anchorage: increasing the number of teeth to the stationary unit, using headgear, retracting teeth individually rather than as a group and using inter-arch elastics. When a force is applied to a bracketed tooth, the net force actually transmitted to the tooth determines the amount of tooth movement. Since the frictional resistance of an appliance determines the net force transmitted to the tooth, altering the frictional and tribological characteristics of the bracket–archwire interface may enable one to control tooth movement, and thus anchorage. Consider for example, a patient who requires premolar extractions and canine retraction with moderate to maximum anchorage. If the frictional resistance at the molar bracket-archwire interface is increased with respect to that of the canine, then the molar will experience less net force and anchorage would be increased.

The use of ceramic brackets, in orthodontics, has become quite popular because of their improved esthetics over stainless steel brackets. Since they are generally placed on the maxillary six anterior teeth, while stainless steel brackets and bands are used on the posterior teeth, the frictional resistance within the appliance would not be uniform. The anterior segment will have increased friction relative to the posterior teeth since ceramic brackets have increased frictional resistance. This may be detrimental when using sliding mechanics, particularly with a maximum anchorage situation. Since the posterior teeth will experience a greater net force, anchorage loss may be inevitable and treatment may be compromised. This fact further emphasizes the importance of controlling the frictional resistance of orthodontic appliances. Perhaps changing the frictional properties of the bracket-archwire interface will provide a method of anchorage control in the future.

4.3 Limitations

Extensive research has investigated the frictional resistance of orthodontic appliances and various methods of applying the normal force at the bracket-archwire interface have been used. The use of stainless steel or elastic ligatures introduced variability in the normal force applied and thus affected the frictional resistance, as previously described. This study overcame this problem by using a 500 gram brass weight connected to a Teflon guide to ensure a constant normal force. This design, however, introduced an interface between the archwire and Teflon guide in addition to that between the bracket and archwire. Thus, the frictional resistance measured by the load cell was the combined resistance of the bracket-archwire interface and the Teflon guide-archwire interface. Consequently, the friction associated with ligation was not completely eliminated by the testing apparatus and this may have represented a limitation to this study. In order to assess the contribution of the friction of the Teflon-archwire interface to the overall friction recorded by the load cell, the coefficients of friction between the Teflon guide and each archwire type used in this study were measured and subtracted from the apparent coefficient of friction means measured in the dry and wet states. The general order of the magnitude of the apparent coefficients of friction and the adjusted coefficients of friction were similar. A few changes, however, were noted. Subtracting the friction of the Teflon-archwire interface resulted in equal coefficient of static friction means for the .016 inch and the .022 inch stainless steel archwire surfaces tested with stainless steel brackets in the dry state. A similar result was seen with .020 inch round wires and the .016 inch flat surface of the stainless steel wires when tested with titanium brackets in the dry state. These findings demonstrate how friction is independent from the apparent area of contact.

The apparatus used in this study ensured a single surface contact between the brackets and archwires so that the normal force would be known and constant. While this provides an ideal situation for the calculation of the various coefficients of friction, it does not truly represent the clinical process of sliding mechanics. As described previously, tooth movement entails oscillating tipping and uprighting as the slot edges of the bracket bind with the archwire. While the normal load applied at the bracket-interface in this study simulated the load when bracket-archwire binding occurs, the pressures between the two situations would not be equal. With bracket-archwire binding, the load is concentrated at opposite edges of the bracket slot and therefore larger pressures would result than those across the larger interface of this study. These increased pressures may result in gouging and notching of the archwire. These phenomena, which were not simulated in this experiment, may reduce the efficiency of orthodontic sliding mechanics and may alter the comparative frictional resistances recorded in this study.

Clinical experience has demonstrated that orthodontic tooth movement occurs at a very slow rate. The mean rate of tooth movement is estimated to be 1 mm/month (2.3 X 10^{-5} mm/min). Although this study calculated both the coefficients of static and kinetic friction, the results from the static frictional coefficients may have a greater significance to the slow and non-continuous tooth movement observed with sliding mechanics.

Although the second part of this thesis demonstrated that saliva generally did not influence friction or provide evidence of stress corrosion, the limitations of this pilot study should be recognized. The limited sample size represents one limitation. More samples may have decreased the variability and thus increased the ability to draw conclusions. The single application of saliva may also be regarded as a limitation, since the fluid dynamics of the oral cavity were not completely simulated. In addition, perhaps the duration of the stationary period in the stress corrosion study was inadequate to initiate this phenonmenon. This may also be regarded as an experimental limitation.

4.4 Recommendations for Future Studies

1. A problem one encounters in comparing the results of the many studies in this area is the lack of standardization in the apparati employed. For example, different methods of ligation invariably lead to differing normal forces and thus influenced the frictional resistance recorded. Inconsistencies were also established in calculating the frictional forces. Not all studies differentiated between static and kinetic friction. The establishment of standardized protocol for friction testing would help avoid some of these variables when investigating the frictional resistance of various orthodontic appliances.
2. This study demonstrated that sliding mechanics with stainless steel wires resulted in less frictional resistance than TMA wires. It was also observed that TMA adhesions remained on the brackets following testing with TMA wires. It would be beneficial to determine whether the adhesions, remaining after testing with TMA, would adversely affect the frictional resistance of stainless steel archwires used with those brackets. This would provide clinical insight since some practitioners may use TMA wires prior to performing sliding mechanics on stainless steel wires.
3. This study determined the coefficients of friction using single surface contacts to eliminate the binding as a factor in frictional resistance. Further research investigating the binding characteristics of titanium brackets may further our understanding of the frictional characteristics of these brackets.

4. The pilot study investigating the influence of human saliva did not tend to display any strong tendencies, except for the decreased kinetic friction for the titanium bracket – stainless steel archwire combination. Recognizing the limitations of this study, such as the fluid dynamics as compared to the oral environment, future research providing a continually wet field may provide different findings.
5. The influence of corrosion on friction was determined to be insignificant under the circumstances of the pilot study. Future research providing an environment more conducive to corrosion, such as the factor of time, may result in different findings and may provide clinically significant findings.

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