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Investigation of frictional resistance on orthodontic brackets when subjected to variable moments

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INVESTIGATION OF FRICTIONAL RESISTANCE ON ORTHODONTIC BRACKETS WHEN SUBJECTED TO VARIABLE MOMENTS

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ABSTRACT

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Friction and binding occur in orthodontics during sliding mechanics. This paper evaluated the influence of a variable moment, simulating mastication, placed at the bracket-archwire interface to determine its effects on friction. Friction of self-ligating brackets were also compared to stainless steel and ceramic brackets. Six archwires were combined with four brackets. Friction (static, kinetic and dynamic) and load (dynamic and apparent stiffness) were measured. Dynamic friction was the frictional force that occurred when the applied force was variable (dynamic load). The results showed that static and kinetic friction were similar while dynamic friction was statistically greater. The Minitwin and Transcend 6000 brackets produced greater friction than the In-Ovation and Damon 2 brackets for all archwires, except with the 19x25TMA archwire. The Damon 2 bracket yielded the least friction. Dynamic friction was momentarily reduced below kinetic friction; thus, releasing the binding and enabling tooth movment.

DEDICATIONS

To my parents, **Bobby and Susanna Mah**, for their enduring love and support. Thank you for allowing me to pursue my goals, to grow as an individual and teaching me to always strive to be the best.

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CHAPTER 1

INTRODUCTION

Background

Orthodontists are always seeking techniques in which to reduce friction during sliding mechanics. Frictional resistance has been primarily studied *in vitro*. The majority of investigators have attached a bracket to a mechanical testing machine that measures frictional resistance. The bracket is ligated to and drawn along a suspended fixed archwire sample. The mechanical testing machine records the amount of frictional resistance that is present as the bracket slides along the archwire. However, this does not fully emulate the clinical reality. When one chews, speaks, swallows, etc., at least several thousand times each day, responsive minute movements of the teeth occur. In addition, when the surrounding tissues, food particles, etc., contact the orthodontic appliance, random asynchronous minute movements occur in the appliance. This results in numerous minute momentary movements at the bracket-archwire interfaces. Previous studies[1] have demonstrated that vibrations at the bracket-archwire interface result in frictional resistance approaching zero.

This study will investigate the frictional resistance of self-ligating, stainless steel and ceramic brackets when variable moments are placed at the bracket-archwire interface. The size and composition of archwires will be varied. The relative frictional forces obtained in this study will be more meaningful when compared with each other, as opposed to an actual force value that might be measured clinically on a patient.

Statement of the Problem

Do variable moments at the bracket-archwire interface influence friction? Do self-ligating brackets exhibit less friction than stainless steel and ceramic brackets?

Significance of the Problem

Frictional resistance has always played a vital role in orthodontics. Its ability to impair tooth movement results in the need for greater forces to move teeth, prolongs treatment time and leads to loss of posterior anchorage. Therefore, sliding mechanics, which is used in all facets of orthodontics, works best when friction is minimized. This investigation will study self-ligating, stainless steel and ceramic brackets in the presence of variable moments at the bracket-archwire interface to determine which yields the least amount of friction.

Hypothesis

There is no difference in frictional resistance between self-ligating, stainless steel and ceramic brackets when subjected to variable moments.

Definition of Terms

apparent stiffness – resistance to moments (stiffness) of an archwire measured when rotating the bracket 20^{o}.

coefficient of friction – the ratio of two forces; the weight (normal force) of an object being moved along a surface and the frictional force that resists movement. The coefficient is independent of the area of contact and independent of the sliding velocity.[1]

conventional bracket – commonly used stainless steel or ceramic brackets that require the use of a steel or elastic tie to enclose the archwire.

dynamic friction – frictional force that occurs when the applied (normal) force is variable (dynamic load).

dynamic load – variable moment occurring with or without archwire pull.

friction – the force that retards or resists the relative motion of two objects in contact; the direction is tangential to the common boundary of the two surfaces in contact.[2]

in vitro – outside the living body and in an artificial environment.

in vivo – within a living organism.

kinetic friction – the force that resists the sliding motion of one solid object over another at a constant speed.[3]

mastication – biting and grinding food in your mouth so it becomes soft enough to swallow; to grind and pulverize food inside the mouth, using the teeth and jaws.

noise – electronic variability within the system.

oscillation – a single swing from one extreme limit to the other and back.

resistance – a force that opposes or slows down another force.

self-ligating bracket – a bracket that completely encloses the archwire without the need for steel or elastic ties.

sliding – to move over a surface while maintaining smooth, continuous contact.

sliding mechanics – the process of an archwire moving through the slot of a bracket to allow tooth movement.

static friction – the smallest force needed to start the motion of solid surfaces that were previously at rest with respect to each other.[3]

stiffness – a combination of modulus of elasticity and moment of inertia

tipping – rotation about an axis perpendicular to the facial surface of a tooth

variable moment – tipping that is not constant (ie. sinusoidal or cyclical pattern)

Assumptions

1) Brackets, archwires and elastic ties of each type are identical in physical attributes and composition.
2) Frictional force needs to be overcome in order to slide brackets along an archwire.

Limitations

1) Force of elastic ties holding the archwire in the bracket slot varies and decays with time.
2) Application of this *in vitro* study to any *in vivo* situation has limitations.

   With any testing situation, it is impossible to reproduce the exact situation one might encounter in the mouth. In the oral environment, saliva amount and content, bacteria type and concentration, types of liquids and solids ingested, force of oral musculature upon chewing, and periodontal health are some of the factors not encountered when performing this study *in vitro*.

3) Out of plane deformations were not evaluated.

Delimitations

1) Only maxillary first premolar orthodontic brackets with 0.022-inch vertical slot and 0.028-inch slot depth will be investigated.
2) Only 0.018-inch nickel titanium, 0.018-inch stainless steel, 0.019 x 0.025-inch TMA, 0.018 x 0.025-inch stainless steel, 0.019 x 0.025-inch stainless steel and 0.021 x 0.025-inch stainless steel will be evaluated.
3) Only injection molded O-ties (Ormco), which are more consistent in size and force, will be used.
4) No 2^{nd} or 3^{rd} order bends will be examined.
5) Amount and frequency of variable moments placed at the bracket-archwire interface will be 1.00 Hz (60 cycles/minute).
6) A final tipping angle of 20^{o} of the bracket will be employed. The resulting force varies with each bracket-archwire combination.

CHAPTER 2

LITERATURE REVIEW

Friction

Friction is the force that retards or resists the relative motion of two objects in contact. Its direction is tangential to the common boundary of the two surfaces in contact[2] and opposite to the direction of motion (Figure 1). When two contacting surfaces are in motion, three force components are present. The first is the force causing the motion, the second is the frictional force, which is opposite in direction of the motion. The other component is the normal force, which is perpendicular to or at right angles to the contacting surfaces and also to the frictional and moving forces. The magnitude of

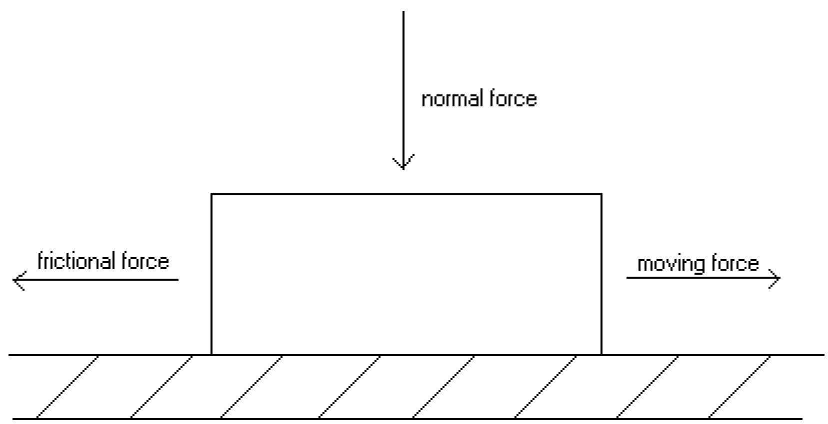

Figure 1. Diagram of frictional forces.

the frictional force is proportional to the normal force that pushes the two surfaces together.[4,5,6,7] Friction is also a function of the relative roughness of the two surfaces in contact.[4,8] Kapur et al. stated that frictional forces are largely due to the atomic and molecular forces of attraction at the small contact areas between materials. As a result, friction is greater between two surfaces of the same material than two surfaces of different materials.[9]

Three general relationships of friction state the following:[10,11,12]

1) the frictional force is proportional to normal force when two materials are sliding against each other. $F = \mu N$. Where F is the frictional force, μ is the coefficient of friction and N is the normal force. This implies that the coefficient of friction is a constant.
2) the frictional force is independent of the apparent area of contact; thus, large and small objects have the same coefficients of friction.
3) the frictional force is independent of the sliding velocity of the objects in contact.

Two types of friction exist, static and dynamic. Each has a coefficient of friction μ_s and μ_d. Static friction is the smallest force needed to start the motion of one solid surface over another. Kinetic friction is the force needed to continue the sliding motion of one solid object over another at a constant speed (i.e. the force that resists motion).[1,13]

The coefficient of friction for a given materials couple is a constant, which may be dependent on the roughness, texture or hardness of the surfaces.[14] The actual frictional force is the product of the coefficient of friction and the normal force. In order for one object to slide against the other, the force application must overcome the static frictional force.[15] The coefficient of static friction is always larger than kinetic friction.[16]

Several factors affect friction of orthodontic appliances. Mechanical variables include:

1) bracket[3,8,13,14,15,17-38]: material, slot width and depth, bracket-archwire angulation and surface roughness.

2) Archwire[3,6,7,8,13,14,17-23,25,26,28,34,39-63]: material, cross-sectional shape, size, stiffness, surface coatings, surface roughness and bracket-archwire clearance.

3) method of ligation[3,8,17,20,24,27,28,39,40,42,44,46,48,49,54,64-80]: steel ligature ties, elastomeric ties and force.

4) orthodontic appliance[17,19,34,46,50]: the number of brackets in series, inter-bracket distance, level of bracket slots between adjacent teeth, forces applied for retraction, sliding velocity and vibration.

Biological variables include: saliva,[6,7,17,19,24,30,33,39,40,53,61,63,76,81,82] plaque,[14] acquired pellicle, corrosion, temperature, mastication,[1,8,14,83,84,85] bite force and tooth mobility.[86]

Once bracket movement has been initiated, subsequent displacement of the bracket relative to the wire requires smaller forces.[17] Storey and Smith[87] developed the concept of optimal forces required for maximum rate of tooth movement with a range of 180 to 240 grams being recommended for permanent canine retraction.

Frictional resistance increases as the number of brackets included in the assembly increases. The static friction recorded for single brackets generally doubled when two premolar brackets were used, indicating a linear increase in frictional forces with number of brackets.[41] Leveling reduces the forces required for retraction of the teeth, because the forces required for overcoming frictional resistance will be decreased.[84]

Wire Size

Most investigators agree that friction increases with increasing wire dimension.[6,8,14,17,19,20,21,22,39-47] This was confirmed by Frank and Nikolai,[8] who also concluded that increased wire stiffness increased friction. A bracket responds to the sliding process with increased friction braking if the vertical dimension of the archwire is increased only minimally or the archwire play in the bracket is decreased.[8,14,19,20,23,40,42,48,84] Sims et al.[88] reported that resistance did not rise exponentially with increasing archwire dimensions. However, Tidy[18] found wire and slot size had no effect on frictional force and that a reduction in wire size and subsequent reduction in wire stiffness, permits greater tipping and hence an increase in binding.[6,14]

Wire Shape

Rectangular archwires generate greater friction than round wires due to the sides and corners of rectangular wires binding the edges of the bracket slot.[8,17,20,40,41,49,51,84,89] Sliding teeth along 0.018-inch round wire rather than rectangular wire is often suggested since it is believed to generate less friction and conserve anchorage.[39]

Ligation

Elastomeric and stainless steel ligation methods of engaging the wire in the bracket slot provide varying ligation force levels and may affect frictional values.[3,8,27,39,43,48,52,54] It has been postulated that the friction between conventional brackets and stainless steel or elastic ligature ties impedes the clinical performance of the new nickel titanium wires, and individual movements of teeth become nearly impossible.[65] Schumacher et al.[66] stated that friction was determined mostly by the nature of ligation and not by the dimensions of the different archwires. Friction is related to the applied normal force, which is influenced by the degree of tension of the ligature engaging the archwire into the slot[24,67,68] and the coefficient of friction between the ligature and the archwire material.[8]

Steel ligatures were found to induce less friction than elastic ligature.[8,23,40,41,52,66,69,70,71] Therefore, pre-expansion is recommended when elastics are to be used.[41] Bednar et al.[52] reported that steel-tie ligated ceramic and steel brackets brackets demonstrated less friction than the elastomeric-ligated ceramic and steel brackets at every archwire size. Andreasen and Quevedo[20] concluded that steel ligatures can be very “clinician sensitive”, and that as the force of ligation increased, the frictional resistance increased.[8,17,24,28,67,72,84,88] However, Riley et al.[40] determined that steel ligatures generated more friction than elastic ligatures, particularly when plastic brackets were used.

Investigations have also shown that elastomeric modules produce a wide variation in force levels.[22,73,74,75] Elastomeric ligatures have been shown to increase friction by 50-175 grams,[22] although this does not necessarily rise exponentially with increasing archwire dimensions.[48] The placing of ‘figure-eight’ elastomeric ties was reported to increase friction by a factor of 70-220% compared to conventional elastomeric ties. Bracket designs that restricted the force of ligation from being placed on the archwire generated lower kinetic frictional forces as compared with bracket designs that did not restrict the ligation force.[88]

Permanent deformation of elastomerics, related to time (stress relaxation), how fast they are stretched[76] and deformation, as a result of hydrolysis due to water and moist heat in the oral environment, were reported to change the degree of frictional resistance.[77,78,79] Therefore, static friction decays over time with elastomeric modules.[41] The rapid rate of decay for these elastomeric ties and their predilection for harboring large quantities of plaque and the resultant decalcification, suggests that there is little merit in their use, especially in translatory movement and sliding mechanics.[70]

Bracket Width

Andreasen and Quevedo[19] and Peterson et al.[20] concluded that bracket width did not affect friction, whereas Nicolls[67] and Frank and Nikolai[8] found that friction increased with wider brackets. Larger frictional forces with wider brackets may be attributed to the higher forces of ligation that result from the greater stretching of elastic ligatures on wider brackets.[17] However, Nicolls,[67] Drescher et al.[14,44] and Tidy[18] found that as bracket width increased, friction decreased due to the reduction in tipping, and hence binding, by the wider bracket. This was confirmed by Garner et al.[21] and Prososki et al..[47]

Bracket-Archwire Angulation

Greater angulation between the archwire and bracket yielded greater friction.[8,19,20,26,50,67,72,80,88] The dependence on angulation is more pronounced in stainless steel than nickel titanium archwires, a possible reason being the lower stiffness of the latter wire.[13] Frank and Nikolai[8] also found that frictional resistance increased in a nonlinear manner with increased bracket angulation. This is more correctly attributable to binding rather than true friction.[72]

Surface Roughness

No definite relationship has been found between archwire and bracket surface roughness and friction.[47,80] The effects of roughness depend not only on the degree of surface roughness but also on the geometry of roughness, orientation of roughness features and relative hardness of the two contacting surfaces. Generally, friction tends to be highest for very rough or very smooth surfaces. Very rough surfaces can cause high friction because of the contact and interlocking of peaks and valleys.[14] Very smooth surfaces make possible relatively large areas of adhesion that tend to grow during sliding. Surface films are powerful modifiers of friction, and they have been found to change friction by as much as a factor of 10.[29,31]

Kusy and Whitley[32] showed that, while the smoothest wire surface did have the lowest coefficient of friction, surface roughness does not necessarily correlate with the coefficient. Laser spectroscopy demonstrated that surface roughness values of various orthodontic wires do not correlate with measured frictional values. A more recent study using a profilometer showed no significant correlation between roughness and frictional forces for various types of archwires.[33]

Other studies have demonstrated that friction increased with bracket slot surface roughness.[80] The significantly lower frictional resistance provided by stainless steel brackets is most likely a result of their lower surface roughness, which is clearly visible when comparing scanning electron micrographs.[30]

Wire Material

The material of the wire affects the frictional resistance produced.[17,18,20,48] Consensus is still lacking pertaining to which wire material, stainless steel, nickel titanium or beta-titanium, yields the most friction. Each of the three wire types have been found to produce the least amount of friction, in at least one study, when compared to the other two wires.

Investigations that pulled a straight piece of wire through orthodontic brackets without any variable moment, found that nickel titanium produced the least amount of friction, followed by stainless steel and then beta-titanium wires.[3,18,14,15,20,33,34,46] However, there are studies that suggest significantly lower friction with stainless steel wires than with nickel titanium or beta-titanium wires.[7,14,17,18,21,30,33,35,39,41,45,48,52,53,57,58,59,72,88] Other studies have found no significant difference in the levels of friction between stainless steel and nickel titanium archwires against stainless steel brackets.[14,17,18,20,21,26,30,35,39,47,48,50]

Beta-titanium was found to exert greater friction when compared to stainless steel and nickel titanium[13,14,17,21,33,35,45,47,53,60] possibly due to the adhesion of beta-titanium archwire material to the brackets. Some investigators have stated that beta-titanium archwires should be avoided whenever sliding mechanics is required. However, a study conducted by Bazakidou et al.[61] concluded that nickel titanium had more friction than beta-titanium. With laser spectroscopy, stainless steel appeared the smoothest, followed by beta-titanium and nickel titanium.[33,47] Despite the fact that laser spectroscopy has found the surface of beta-titanium to be smoother than nickel titanium,[62] most studies show that beta-titanium wires generate more friction than nickel titanium wires.[14,17,35,39]

Saliva

The presence of saliva had an inconsistent effect on the static frictional resistance, in some cases with saliva functioning as a lubricant and at other times acting to increase friction.[63] Investigators evaluating stainless steel brackets suggested that friction might increase,[7] decrease[67] or not change[19] when tested in saliva.

Stannard et al.[7] reported that saliva increases frictional resistance rather than acting as a lubricant, and this was also confirmed by other investigators.[7,30,39,40,60,62,63] This finding contradicts the general perception of saliva as a lubricant for archwires and brackets. Water and other polar liquids are known to increase adhesion or attraction among polar materials and thus increase friction.[7] Baker et al.[6] showed a reduction in friction between 15% to 19% under the presence of a saliva substitute (Xero-Lube). This was confirmed by Kusy,[32] Lorenz[75] and Thurow.[81]

In the dry or wet states, the static and kinetic coefficients of friction were often higher with ceramic than with stainless steel brackets.[53] In another study, when ceramic brackets were tested, artificial saliva increased the friction whereas human saliva caused a decrease.[30] The greatest difference between dry and wet states occurred with beta-titanium archwires, in which the kinetic coefficients of friction in the wet state were reduced to 50% of the values in the dry state.[53]

The explanation for the discrepancies in results may lie in the significance of the loading forces used between the archwire and the brackets. At low loads saliva acts as a lubricant, but at high loads saliva may increase friction if it is forced out from the contacts between the brackets and the archwire. In the latter situation, saliva may produce shear resistance to sliding forces.[7,30] It was also stated that archwire alloy and saliva seem to dictate frictional characteristics, which has been shown before.[17,32,53]

Stainless Steel Brackets

Stainless steel brackets exhibit lower frictional resistance than mono- or polycrystalline ceramic brackets.[30,35,60,80,82] Vaughan et al.,[89] Kapila et al.[17] and Angolkar et al.[39] demonstrated that sintered (metal injection molded, MIM) stainless steel brackets generated 40 to 45% less friction than cast stainless steel brackets. Scanning electron micrographs of sintered brackets demonstrated a smoother bracket surface due to the sintering process. Sintering allows each individual bracket to be pre-molded in a smooth streamlined manner. The stainless steel particles are then compressed into a contoured, smooth, rounded shape as opposed to other procedures where the milling or cutting process may leave sharp angular brackets that are more bulky and rough.[89]

Stainless steel wires created more friction with stainless steel brackets than with ceramic brackets. This was confirmed by Kusy and Whitley[35] and Spiller et al..[50]

Ceramic Brackets

Ceramic brackets were developed to improve esthetics during orthodontic treatment. Those with a ceramic slot generated more friction than those with a stainless steel slot[6,30,36,53] and stainless steel brackets.[15] This is most likely due to the increased roughness and porosity of the ceramic surface[30,39,52,53,55] and a sharp bracket slot edge[3] thus, resulting in a higher coefficient of friction. Monocrystalline ceramic brackets have smoother surfaces than those of polycrystalline, but the observed amount of friction appears to be similar.[45,62] Likewise, ceramic materials have a rougher and more porous surface than stainless steel[30,55] and may even abrade the archwire because ceramics are harder than stainless steel.[36] Scanning electron micrographs at 650x showed that the polycrystalline structure of the ceramic bracket (Transcend 2000/3M Unitek) was evident, varying from irregular to polyhedral in form with the surface also containing many pores. The ceramic bracket with stainless steel slot showed the surface finish to be smoother with fewer irregularities than the ceramic bracket slot.[55] Therefore, greater force is needed to move teeth when using ceramic brackets with no stainless steel slot.

Riley et al.[43] stated that stainless steel ligating could compress the stainless steel bracket slot and therefore increase friction. The binding between the ligatures and the rough ceramic surface can also result in increased friction. Other investigators suggested that the major cause of the increased resistance of ceramic brackets is due to the difference in surface hardness between the ceramic material and stainless steel, beta-titanium or nickel titanium wires.[3,32,35,39,45,90,91,92] The Transcend 2000 bracket, cut with diamond tools, has sharper and rougher sliding edges, and was found to scribe grooves into the wires.[3] Rounding the slot corners of ceramic brackets significantly reduced the resistance of the brackets to archwire sliding.[93]

Some studies failed to detect any differences in frictional forces between ceramic and stainless steel brackets.[18,32] One study found that polycrystalline ceramic brackets produced similar frictional forces to stainless steel brackets when using stainless steel or nickel titanium wires. Therefore, there would be no disadvantage to using ceramic brackets when teeth require sliding.[55] However, some of those studies used models that did not simulate the initial tipping and rotation movements that occur clinically. The wires may not have contacted the bracket slot edges during the entire course of the experiment; thereby, reducing the potential for detecting differences. DeFranco et al.[34] confirmed this theory. At 0^{o} angulation, with minimal potential for contact between brackets and archwires, only minor differences in frictional forces were detected. With increased angulations, however, which ensured bracket and archwire contact, friction was significantly higher with the ceramic brackets.

Ceramic brackets are associated with several problems, such as fracture during torsional and tipping movements,[94-98] abrasion on opposing teeth,[39,99,100] iatrogenic enamel damage during debonding[95,101,102,103] and increased frictional resistance in sliding mechanics (polycrystalline or monocrystalline alumina), when compared with stainless steel brackets.[3,30,36,37,43,46,50,53,58,62,104,105] There have been several improvements in recent years to reinforce ceramic brackets, such as precision-made stainless steel slot inserts.

<u>Self-Ligating Brackets</u>

Self-ligating brackets address two important concerns for orthodontists. A decrease in frictional resistance, both static and dynamic, has to benefit the hard and soft tissues, whereas a decrease in the time of archwire removal and insertion addresses both ergonomic and economic considerations. The self-ligating bracket systems are also advantageous in that they do not promote poor oral hygiene, as with elastomeric ties, and eliminate any chance of soft tissue laceration to both the patient and the orthodontist from the use of stainless steel-tie wires.[70] The self-ligating bracket allows the clinician to spend less time with the patient.

The concept of a ligatureless edgewise bracket first appeared in 1935 with the Russell Lock appliance.[59,106,107] The idea of a ligature-free system was further refined by Wildman with his introduction of the Edgelok appliance in 1972. The mechanism for retaining the archwire involved sliding a labially positioned cap across the top of the archwire slot and into the locked position, thereby creating a rectangular slot, or tube, within which the archwire had total freedom of movement. The Mobil-Lock bracket was introduced in 1980. Hanson,[108,109] also in 1980, created a spring-loaded, self-adjusting ligatureless design that possessed the unique quality of retaining and actively influencing control of the archwire within the archwire slot. This was called the SPEED appliance. In 1986, the Activa bracket was designed and in 1994 the active Time bracket was introduced. Damon in 1996 designed the passive self-ligating Damon SL bracket. When the slide is closed, the lumen of the slot is full-size, which is critical for rotational control. The passive Twinlock appliance, also designed by Wildman, was introduced in 1998. Damon redesigned the Damon SL bracket and introduced the passive Damon System II bracket in 2000. Voudouris also designed a new active self-ligating bracket named In-Ovation in 2000.

All the inventors report a significant reduction in the level of friction, in addition to shorter treatment time and chair-time, when compared with conventional bracket systems.[68,110,111] The fact that similar advantages were noted 47 years earlier with the use of the first Edgewise self-ligating bracket, the Russell Lock,[106] lends a certain degree of credence to these current observations.

Sims et al.[88] found that self-ligating brackets produced substantially less friction than conventional elastomerically tied brackets, using archwires ranging from 0.016 x

0.022-inch to 0.019 x 0.025-inch.[59,70,88,112,113] Ligating clips of the self-ligating brackets possess a smaller magnitude of force pressing the archwire into the bracket slot relative to the steel or elastomeric ligatures of the conventional systems.[58] Therefore, less force is required to produce tooth movement because they apply less friction to the archwire than conventional tied Siamese brackets.[88]

Voudouris[65] compared the friction produced by three types of conventional twin brackets compared to three types of self-ligating brackets: one active (Sigma) and two passive (Damon SL and Wildman TwinLock). When 0.019 x 0.025-inch stainless steel wires were drawn through the brackets, friction values from highest to lowest were: conventional twin brackets ligated with O-rings, brackets ligated with metal ligatures, active self-ligating brackets and passive self-ligating brackets. Berger et al.[23] found that self-ligating brackets produced less friction than elastomeric or steel-tie ligated brackets.

SPEED Bracket

With the SPEED bracket, the inclined resilient spring clip forms the outer labial wall.[70,88] The aim of active ligation is to seat the archwire against the back of the bracket slot for rotation and torque control. Some active clips are active only with larger archwire sizes; in their passive state, the archwire freely moves within the lumen. The smaller the lumen of the archwire slot, the greater the friction when using a light wire in a distorted occlusion. Friction is also greater with sliding mechanics when a larger working wire is used and the archwire is actively seated to the base of the slot, because the flat surface of the rectangular wire contacts the flat surface of the slot base.[65]

Self-ligation contrasts the inflexible ligature tie wire or an elastomeric tie with a degree of tension related to the decay rate of the polyurethane material. In comparison, a steel ligature tie wire not only binds the archwire on both the mesial and distal aspects of the bracket body but, should the cut end of the steel-tie wire be left in contact with the archwire, then the degree of frictional contact is further enhanced. An elastomeric ligature obviously also hugs the archwire on either side of the bracket's archwire slot and does not permit the degree of archwire freedom observed in self-ligating brackets.[113]

Berger et al.[113] concluded that a lower level of applied force was required when the SPEED bracket was used, regardless of which type of archwire was used. This was true both at the time of the initial loading and again during continuous translation. SPEED self-ligating bracket systems displayed a significantly lower level of frictional resistance, dramatically less chair-time for archwire removal and insertion, and promoted improved infection control, when compared with polyurethane elastomeric and stainless steel tie wire ligation for ceramic and metal twin brackets.

Other investigations have also shown that SPEED brackets produce a reduction in friction when compared to conventional brackets ligated with elastomeric or steel-ties.[41,113] When the SPEED bracket was compared to Minitwin brackets, the reduction in friction was by 50-70%.[88] Berger,[113] in examining both static and kinetic friction, found that SPEED brackets showed dramatically lower initial force levels, followed by an almost constant low level of force during continuous translation as compared with other orthodontic bracket-archwire systems, irrespective of the means of ligation. However, another study found no differences in frictional resistance between the SPEED bracket and a conventionally ligated twin bracket.[70]

The reduction in friction for SPEED brackets compared to conventional brackets only occurred under certain conditions. SPEED brackets demonstrated low forces with round wires, although with rectangular wires or in the presence of angulation, friction was greatly increased.[13,63] In other words, frictional forces increased in a stepwise progression through the increasing wire sizes.[113] This is probably due to the slot depth and the active spring design. The effect of the flexible coverage depends on the presence and absence of contact between the wire and spring, and thus is dependent on the surface structure of the wire and the force delivered by the spring.[13,88]

Bednar et al.[52] found the mean frictional values for self-ligating SPEED brackets were similar or greater than elastomerically ligated stainless steel brackets. They felt that despite the self-ligating clip design inherently decreasing friction, once the tooth tipped during translation, it was the reduced width of the SPEED bracket that determined the increased frictional resistance. The static and kinetic frictions for SPEED brackets were similar. This indicates that once initial tooth movement occurs, a relatively large force is still required to maintain tooth movement.[41]

<u>In-Ovation Bracket</u>

Fabricated by GAC, this bracket is very similar to the SPEED bracket, in that an active clip is used. However, the In-Ovation bracket has tie-wings, which the SPEED bracket does not; therefore, allowing elastomeric ties to be engaged.

Damon SL Bracket

Dr. Dwight Damon designed the Damon SL bracket to satisfy the following criteria: Andrews straight wire appliance concept, twin configuration, slide forming a complete tube, passive slide on outside face of bracket and brackets opening inferiorly in both arches. He also concentrated on five other major areas: improving treatment quality and control, dramatically increasing patient comfort, decreasing treatment time and decreasing chair-time with longer appointment intervals. The goal of the Damon SL system is to minimize friction at all stages of treatment. Configuring the slide as a complete tube enhances torque control, reduces friction, and keeps a light initial wire from "radiusing" from tie-wing slot to tie-wing slot in an extremely distorted occlusion. Torque is always fully expressed in the Damon SL, since the continuous slot forms a complete tube. The archwire must be completely engaged, or the slide will not close.[65]

The self-ligating Damon SL produces a reduction in friction. Teeth drift in the path of least resistance. The brackets of the Damon SL system serve as mini-lip bumpers, especially in the leveling phases. They are more effective in their sliding mechanics than conventional brackets.[114] The Damon SL bracket exhibits even less friction than the SPEED bracket with respect to all wire types due to its passive slide.[13,88,113]

The self-ligating Damon SL bracket demonstrated the lowest friction for all dimensions of test wires when compared to A-company standard twin brackets, which produced the highest friction with all wire dimensions tested.[13,59,112] These results corroborate the findings of previous studies of self-ligating brackets.[58,70,113]

The low friction related to the Damon SL bracket reflects the lack of normal force in these brackets. This accounts for the negligible friction at zero degrees found in some studies.[113] These results indicate that self-ligating brackets require less force to produce tooth movement than conventionally tied Siamese brackets.[88]

Difference in bracket friction may be due to design and manufacturing features. The Damon SL has a locking spring-clip slide over the slot that holds the archwire securely in place. Unlike the conventional elastomeric ligature, this slide allows the wire to lie passively in the slot, reducing the normal component of force. Damon SL shows smoother surface detail than the Minitwin. Although both brackets are manufactured from 17-4 PH stainless steel, the Damon SL bracket is made by metal injection molding, while the Minitwin is investment cast. Binding between the wire and bracket exist in the Minitwin bracket, due to the sharper mesial and distal edges of the bracket slot. This causes point contact between the wire and bracket and allows the wire to be held more tightly in the slot by the elastomeric ligature.[112]

Damon System 2 Bracket

The new Damon 2 bracket has a 35% decrease in bracket width, a gate that is now on the inside and a lower profile.[115]

The list price for the Minitwin, Transcend 6000, In-Ovation and Damon 2 brackets were \$8.15, \$16.50, \$15.00 and \$14.75, respectively. The Minitwin bracket was about half the price of the other 3 brackets.

Sliding Mechanics

Sliding mechanics involves a relative displacement of wire through bracket slots and whenever sliding occurs, frictional resistance is encountered. This technique is commonly used in orthodontics in achieving closure of extraction sites, distalization of teeth, eruption of high cuspids, rotations, leveling and changing arch forms. Frictional forces developed between the bracket and archwire opposes such movements. The consequent decrease in force available for tooth movement results in inhibition of tooth movement,[3] requirement for larger retraction forces and anchorage taxation. Up to 60% of the applied force is dissipated as friction,[116] which reduces the force available for tooth movement.[113] High levels of bracket-archwire friction may result in binding of the bracket accompanied by little or no tooth movement.[55] This higher frictional resistance requires an increase in the magnitude of orthodontic forces needed to overcome the friction, yet have enough residual force for optimal tooth movement. Therefore, orthodontists are always seeking techniques to reduce or even eliminate friction.

In addition, as a result of appliance inefficiency and friction, it is difficult to determine and control the magnitude of force that is being received by the individual tooth.[117] Quinn and Yoshikawa[118] concluded that the rate of tooth movement increases with increases in applied force up to a point, after which additional force produces no appreciable increase in tooth movement. Schwartz,[119] stated that a force as light as that of capillary blood pressure (20-26 gm/cm^2) would produce tooth movement.

Proffit[26] proposed that the optimum force levels for orthodontic tooth movement would be just high enough to stimulate cellular activity without completely occluding blood vessels in the PDL. If a force is great enough to occlude the blood vessels and cut off the blood supply, a hyalinized, avascular area is formed that must revascularize before teeth can move. Pain is related to the development of ischemic areas in the PDL. Tuncay suggested that oxygen is the trigger mechanism in the periodontium. According to Proffit,[26] if vascularity is critical to tooth movement, there is no doubt that light, continuous forces produce the most efficient tooth movement and that heavy forces should be avoided. Rygh recommended light, continuous forces for more effective tooth movement in areas with cortical bone or bone with few marrow spaces. Warita[63] compared the application of a light, continuous force (5 grams) versus a light, dissipating force (10 grams) for 39 days on rat molars. He found 1.8 times greater tooth movement with the light, continuous force.

Static friction is more important in tooth movement than kinetic friction. The coefficient of static friction is always larger than kinetic friction. A high proportion of the force used in tooth movement is lost due to static and sliding friction in the bracket-archwire complex.[69] The static and kinetic frictional forces generated between brackets and archwires during sliding mechanics should be minimized to allow optimal tooth movement.[120] Drescher et al.[14] reported that under low velocity conditions, both static and kinetic friction occur.

Orthodontic forces are typically applied at a distance from the center of resistance of the teeth.[15] In the interaction between tipping and uprighting, rotation and derotation, the bracket and thus the tooth “slides” into swinging movements, though constrained by the friction, along the archwire. In these interactions, the extent of force loss due to friction is proportional to the vertical and horizontal pressure of the archwire in the bracket-archwire complex, which for its part depends on the amount of orthodontically applied force.[121] Translatory tooth movement along an archwire is not continuous, but occurs as a series of small tipping and uprighting movements.

Average PDL space in human beings is about 0.2 mm, and teeth in function tend to have a wider space, particularly in the cervical and apical portions. During periods of orthodontic tooth movement, the distance between the root surface and the alveolar socket may double or triple. Due to the width and compressibility of the PDL, the teeth will therefore tip until contact is established between archwire and diagonally opposite corners of the bracket wings, and rotate until contacts are established between the archwire and ligature or labial bracket cover. These movements occur immediately on force application and before sliding of the teeth along the archwire.[15] The binding between the bracket and archwire stops further crown movement until either wire displacement, tooth mobility or subsequent remodeling releases the binding. Each time the tooth moves a little, the static frictional resistance must be overcome, and kinetic friction occurs.[8] Provided the archwire does not deform, the teeth will maintain the slightly tipped and rotated positions and slide parallel along the archwire.

Orthodontic mechanics attempts to move teeth efficiently; however, atraumatic remodeling of periodontal tissues is rarely achieved. During tooth movement, the remodeling periodontium exhibits changes in the gingiva, periodontal ligament and bone. Oppenheim and Sandstedt[122,123] hypothesized that the suffocation of the periodontal ligament is the triggering mechanism behind the changes seen in bone; the undermining and frontal resorption. Inhibition of synthesis of inflammatory mediators, with aspirin-like drugs, resulted in significant (50%) reduction in tooth movement rate.[124,125] The inflammatory response requires significant vascular activity, as does remodeling. The squeezed periodontal ligament space becomes devoid of oxygen, and this hypoxic condition is abruptly reversed by the proliferating blood vessels that invade the injured regions.[126]

Changes in blood supply can be observed in the human gingiva when subjected to variable moments, either with tooth brushing[127] or orthodontic tooth movement.[128] It has been suggested that the resistance of gingival tissues to remodeling is more important than that of bone for tooth movement efficiency.[129] Changes in vascular supply to all three structures of the periodontium are the critical common triggers for remodeling. The challenge for the orthodontist is to place enough pressure to stimulate cellular activity without occluding the vascular supply in the periodontium.[26] Beginning the treatment with low force, low friction and small dimension wires will allow teeth to move more individually, even though they are connected in a group.

It has been suggested that the resistance to tooth movement, *in vivo*, is not governed by the classical laws of friction, but is a product of the binding and releasing phenomenon at the bracket-archwire interface. This seems to suggest that bracket-archwire sliding *in vivo* is much more dynamic than at first imagined. The effect that mastication and tooth mobility has on this process is not fully understood and little is known about the magnitude of tooth mobility that is required to release binding once it has occurred.[114]

Hixon et al.[130] reported that less force was needed intraorally than extraorally to move the bracket-archwire test apparatus. He contributed this difference to oral forces, especially from mastication, which produced other motions and permitted the wire to slide through the tube more easily. This was confirmed by Jost-Brinkman and Meithke[86] and Andreasen and Quevedo[19] who recognized that relative movement within the periodontium, enhanced by mastication, tended to decrease friction, and as the periodontal ligament spaces enlarged during orthodontic movement, frictional resistance is further reduced. Thurow[81] suggested that relatively minute movements of teeth in function provided a "walking" effect that allows a bracket to move along an archwire more easily.

<u>Variable Moment</u>

Until Liew's[85] study in 1993, all frictional resistance measurements were conducted in a steady state, absent any vibrations or disturbances at the bracket-archwire interface that would be produced by various oral functions. He placed vertical displacements on the archwire under differing loads using low frequency (91.3 cycles/minute) vibrations. He found that the resistance to archwire movement through an orthodontic bracket was decreased by continuous repeated vertical displacement of the wire. This reduction was as great as 85% for loads in the range 100-250 grams, while loads as small as 25 grams reduced friction by more than 50%. Therefore, several investigators have reported that forces required to overcome friction, clinically, are less than those measured in steady-state laboratory experiments,[80,131] due to mastication and tooth mobility.

O'Reilly et al.[1] studied 0.022 x 0.028-inch maxillary premolar stainless steel brackets with 0^{o} tip and 0^{o} torque. Four different archwire types were investigated: 0.016-inch stainless steel, 0.019 x 0.025-inch beta-titanium, 0.019 x 0.025-inch stainless steel and 0.021 x 0.025-inch stainless steel. An alignment fixture was used to ensure that the bracket was placed at the center of each block and the bracket slot was at right angles to the surface of each block.

The apparatus consisted of two parts: a lower member swivel mounting, which supported the test bracket and an upper member slide that supported the fixed brackets and the test archwire. The distance between the two brackets on either side of the window measured 19.2 mm, which is the average distance between a lateral incisor bracket and a second premolar bracket. The test bracket was then placed in the window and the test wire was then placed through all four brackets in series.

A vibrating machine produced the bracket displacement. A frequency of 1.35 Hz (81 cycles/minute) was used, which simulates normal chewing. The crosshead speed of the archwire through the bracket slot was 1 mm/minute. An Instron universal testing machine was used to measure the forces encountered during the study. Each test run lasted one minute and the loads were recorded in newtons. Four amplitudes were chosen for investigation ranging from 0 mm to 1.0 mm. A total of 16 cohorts (four wires and four amplitudes) with 20 specimens in each group were assembled.

This study concluded that the effective sliding resistance between orthodontic brackets and archwires is substantially reduced by repeated displacement. The reduction in sliding resistance noted with displacement, depended on the archwire.

Braun et al.[83] also performed an investigation involving deflection of the archwire in bracket slots. Two types of 0.018-inch slot brackets, Ormco standard canine and premolar brackets, were used. Three archwires were studied: 0.016-inch stainless steel, 0.016 x 0.016-inch stainless steel and 0.018 x 0.025-inch stainless steel. A bracket-holding jig was fabricated to allow for changes in the bracket angle relative to the archwire. The bracket angulations relative to the archwire were tested from 0^{o} (as in translatory movement) to a maximum of 25.5^{o}, as in dental tipping.

The crosshead speed was 0.1 mm/minute and all tests were conducted in a dry environment. Steel ties (0.010-inch) were used to hold the archwires in the bracket slots. Deflections were applied to the bracket or archwire in random frequencies and in random directions in all three planes of space. The deflections were applied with finger touch, measured by a Correx gauge, to the bracket or archwire with a mean force of 87.2 grams (range 20 to 200 grams).

This study concluded that frictional resistance momentarily became zero in 96% of the experiments. This reduction seemed to be independent of the archwire size in the 0.018-inch slot brackets tested. The use of steel or elastomeric ties had no apparent influence. Relative bracket-archwire angulations up to 25.5^{o}, in the presence of oscillations, did not increase frictional resistance.

Kapur et al.[112] investigated frictional resistance on Damon SL and Minitwin brackets without deflections in the archwire. All brackets were 0.0225 x 0.030-inch maxillary first premolar brackets. The wires used were 0.018 x 0.025-inch nickel titanium and 0.019 x 0.025-inch stainless steel. Each bracket was bonded perpendicular to a cylindrical jig, which was then fixed in a specially designed apparatus. The apparatus was secured to the base of an Instron universal testing machine. The wire was attached to a tension load cell on the crosshead of the testing machine. Each test was conducted for two minutes at a crosshead speed of 0.02 inch/minute. Frictional forces were measured and analyzed using the Statistical Analysis System program. The results revealed that the Damon SL bracket had lower kinetic frictional forces than the Minitwin bracket with both wires.

Drescher et al.[116] investigated changes in friction with respect to archwire material, archwire size, bracket width and biologic resistance. A friction-testing assembly simulating three-dimensional tooth rotations was constructed to study factors affecting friction magnitude. Five wire alloys (standard stainless steel, Hi-T stainless steel, elgiloy blue, nitinol and titanium molybdenum alloy) in five wire sizes (0.016, 0.016 x 0.022, 0.017 x 0.025, 0.018 and 0.018 x 0.025-inch) were examined with respect to three bracket widths (2.2, 3.3 and 4.2 mm) at four levels of retarding force (0, 1, 2 and 3 Newtons). The results yielded the following factors to affect friction in decreasing order: retarding force (biologic resistance), surface roughness of wire, wire size (vertical dimension), bracket width and elastic properties of wire.

Omana's[3] study compared the frictional effects of seven brands of ceramic brackets (Starfire, Contour Twin, Allure IV, Lumina, Illusion, CeramaFlex and Transcend 2000) to those of a similar type of metal bracket (Mini Diamond). Each bracket was tested on 0.018 x 0.025-inch straight pieces of nickel titanium and stainless steel wires. Load ranging from 50-150 grams were randomly placed on a 10 mm long counterweight arm to simulate the effects of varying amounts of bracket engagement during tooth movement. As the wire was drawn through the bracket, the static frictional forces were measured by an Instron machine.

The results showed that increasing levels of bracket engagement (load) resulted in a corresponding increase in frictional force, there was no appreciable difference between the frictional force values of the stainless steel and nickel titanium wires. In addition, smoother, injection-molded ceramic brackets appear to create less friction than other ceramic brackets, wider metal or ceramic brackets create less friction than narrower brackets of the same material and excessive force is counterproductive because of increased bracket friction and potential loss of posterior anchorage.

In vitro frictional resistance experiments that did incorporate variable moments at the bracket-archwire interface concluded that the relationship between displacement and friction appears to be linear. The effect of displacement was shown to have a significant effect on sliding resistance regardless of wire type.

Earlier investigators suggest that increased relative bracket-archwire angulations will produce greater vertical reactive forces at the interfaces and thus increased frictional resistance.[8,50,80] However, relative bracket-archwire angulations up to 25.5^{o}, in the presence of oscillations, did not increase frictional resistance. Although, it should be noted that relative archwire stiffness, and consequently the related response to random oscillations, is affected significantly by the archwire length defined by the location of the end supports.[83]

If one considers the clinical situation, where there is intermittent movement between the bracket and archwire, then clinically we may not be looking at true friction, but rather a binding and releasing phenomenon. Kajdas et al.[132] found that repeated displacement of a bracket, equivalent to as little as 0.16 mm of mesio-distal crown movement (which is within the range of normal tooth mobility), could reduce the sliding resistance by as much as 85%. Assuming this fact, it is not unreasonable to conclude that the reduced sliding resistance observed *in vivo* may be a result of this intermittent movement between the bracket and archwire.

Braun et al.[83] concluded that frictional resistance was effectively reduced to zero each time minute relative movements occurred at the bracket-archwire interfaces. Variable moments, although an inexact replication of those occurring in the oral environment, resulted in frictional resistance to momentarily become zero. This reduction seemed to be independent of the archwire size in the 0.018-inch slot brackets tested. The use of steel or elastomeric ties had no apparent influence. Factors such as the degree of dental tipping, relative archwire-slot clearances, and methods of tying, did not have a measurable effect on frictional resistance in the simulated dynamics of the oral environment. These findings contradict the studies performed in which no variable moments were placed at the bracket-archwire interface.

Contact Angle

The angle needed before the archwire and bracket bind is called the contact angle. Archwires with larger dimensions result in smaller contact angles than archwires with smaller dimensions, when using the same bracket. Kusy[133] created a formula that would calculate the contact angle.

$$\underset{\text{(2nd order angulation)}}{\text{Contact Angle } (\theta_c)} = \frac{57.3\,[1-(\text{size}/\text{slot})]}{(\text{width}/\text{slot})}$$

size = the archwire dimension that contacts the floor of the slot

slot = the bracket dimension at the floor of the slot

width = the mesial-distal dimension of the bracket

Chewing Cycle

Chewing is an alternating rhythm of isotonic and isometric contractions governed by a central pattern generator in the brain stem.[134] This rhythm is continually modified, both voluntarily and in response to factors such as food hardness and bolus position.[135,136] Cases with normal occlusion demonstrate no significant differences in masticatory muscle activity between either the right and left or the working and nonworking sides.[135] A more simple and regular pattern of chewing is seen, compared to cases with malocclusion. The frequency of masticatory contact, which is only one causal component of the minute relative motions at the bracket-archwire interface, has been measured from 32 to 146 cycles per minute.[26,137] The literature indicates that the enamel contact time is about 0.22 seconds.[138] Direct tooth contact during mastication only occurs during the last half of the sequence of masticatory cycles.[137]

During chewing, intact teeth show considerable cuspal flexure, due to tooth morphology and mandibular movement. Typically the buccal and lingual cusps flex in the coronal plane because of the relatively large thickness of the buccal and lingual enamel plates and the thinness of the enamel at the bottom of the central fossa. Conversely, the incisor teeth flex in the antero-posterior plane, where the cross section is thinnest. Of course, cuspal flexure is profoundly influenced by restorative procedures, and control of cuspal flexure by material choice, cavity design and bonding mechanisms.[139]

The elevator muscles consist of the anterior temporalis, posterior temporalis, masseter and medial pterygoid muscles. The posterior temporalis muscle is responsible for occlusion of the teeth, and individuals with large overbites have this muscle strongly activated. The medial pterygoid muscle initiates the closing movement. Both the medial pterygoid and masseter muscles direct and stabilize the mandible towards the side of the bolus in the first part of the closing phase. The elevators produce the force necessary to penetrate and crush the bolus.

The lateral pterygoid muscles move the condyle forward and contralaterally. The depressor muscles consist of the digastric and mylohyoid muscles. The muscles responsible for the opening movement during chewing are activated in the following sequence: the mylohyoid, the digastric and the lateral pterygoid muscles.

Tooth contact is made simultaneously or shortly after maximal activity of the anterior temporalis muscle. It is maintained for about 70 milliseconds after the activity has ceased. Contact between the upper and lower teeth lasts 125 to 150 milliseconds in each chewing stroke, or about 20% of its total duration. The period of tooth contact is not a static situation. Molar contact, consisting of a large range of lateral and ventero-dorsal positions, is made and broken before incisor contact, consisting of intercuspal and slight lateral and protruded positions. Tooth contact is thus divided into 3 stages: first on the molars, then in all areas and finally confined to the incisors.[140]

It has been shown that the bite force varies from one part of the oral cavity to another. The greatest force is exerted in the region of the first molars and is less anteriorly in the mouth. The force at the incisors is only about one-third to one-quarter of that in the region of the molars. The bite force measured with the mandible in extreme lateral positions, in protrusion and in retrusion is much lower than that measured in intercuspal position. Individuals whose diet consists of hard foods have been found to possess a stronger maximum bite force.[141]

An individual pattern exists with regards to mandibular movements in adults. The masticatory movements in a given individual differ from each other.[142] Men have a stronger bite force and shorter chewing cycle with faster velocities than women.[143] Bite force is weakly correlated with general muscle force and skeletal dimensions. The forces exerted during chewing are, as a rule, substantially lower than the seldom used maximal bite force capacity. It has been found that kindergarten children have almost the same amount of bite force as adults. Lindqvist and Ringqvist studied eleven-year old children who grind their teeth resulting in atypical abrasion facets. They found that maximal bite force was not significantly higher in children that brux than in controls without signs of bruxism.[141] Akinson and Shepherd observed a disturbed rhythm and an irregular pattern of chewing in patients with TMJ dysfunction.[142]

CHAPTER 3

MATERIALS AND METHODS

Overview

This research study investigated the effects of variable moments on friction. Different brackets and archwires were used in combination to evaluate the amount of static, kinetic and dynamic friction present. Friction is the load necessary to pull the archwire through a bracket. The load (force) required to tip the bracket to create a constant bracket-archwire angulation was measured. Two types of load were evaluated: dynamic and apparent stiffness. The testing apparatus consisted of a friction-testing device, Instron universal testing instrument, two load cells, two signal amplifiers, two computers and a rotating cam (Figure 2). The Instron machine engaged one end of the vertically oriented archwire, which was inserted in the bracket slot, and it pulled the archwire superiorly. Each bracket-archwire combination was tested 5 times, which yielded friction and load data. During the 60 second trial, the archwire was pulled with and without any variable moments. Variable moments were also measured with and without archwire pull. The data was analyzed to determine which brackets and archwires yielded the most static, kinetic and dynamic friction.

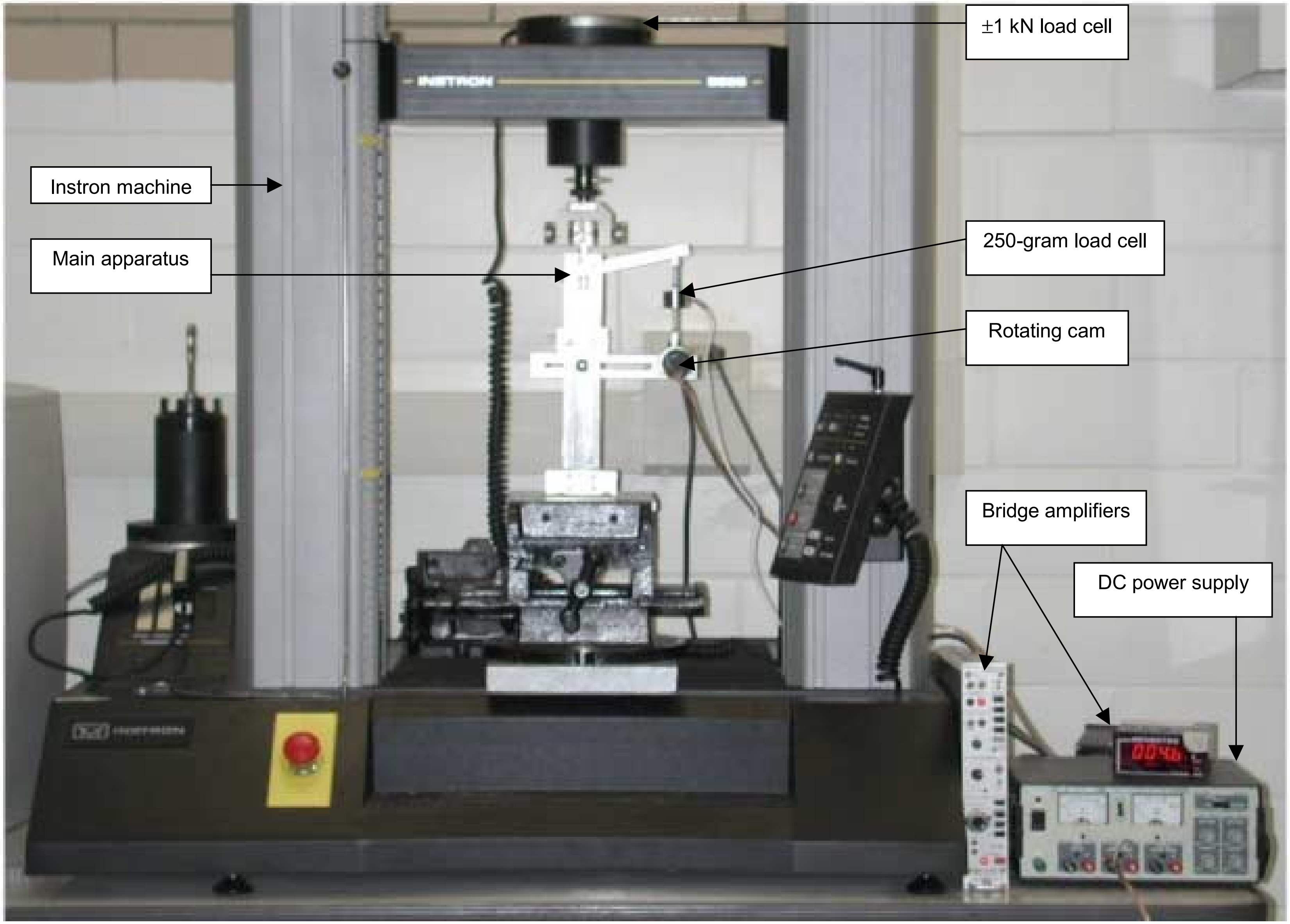

Figure 2. Friction-testing apparatus.

Materials

Maxillary right first premolar brackets with 0.022 x 0.028-inch slots were selected for this study. The brackets were:

1) Minitwin (Unitek) –7^{o} torque, 0^{o} tip (Lot #011254600) (Figure 3).

2) Transcend 6000 (Unitek) –7^{o} torque, 0^{o} tip (Lot #010563600) (Figure 4).

3) In-Ovation (GAC) –7^{o} torque 2^{o} tip (Lot #1101) (Figure 5).

4) Damon 2 (Ormco) –7^{o} torque, 2^{o} tip (Lot #01E742E) (Figure 6).

Figure 3. Minitwin premolar bracket (Unitek).

Figure 4. Facial surface of Transcend 6000 bracket (Unitek).

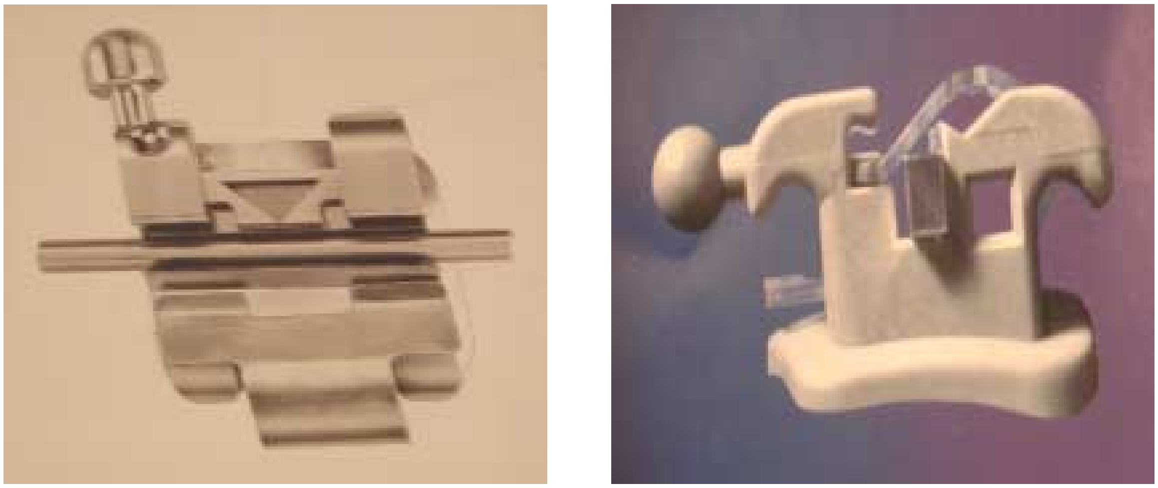

Figure 5. In-Ovation brackets (GAC). Left, Facial surface; Right, Profile view.

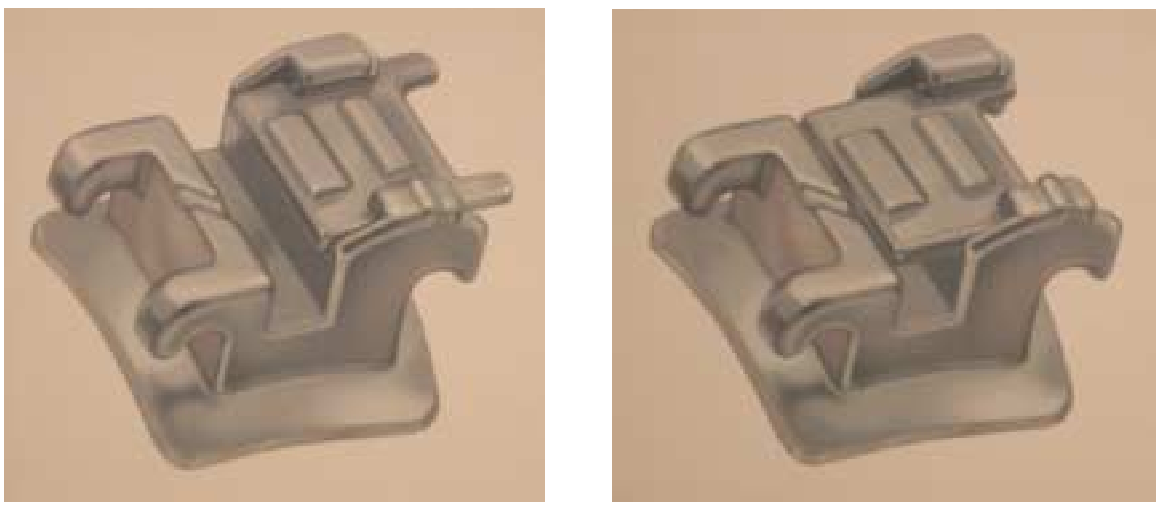

Figure 6. Damon 2 brackets (Ormco). Left, Open slide; Right, Closed slide.

All the archwires used in this study were from Ormco:

1) 0.018-inch round nickel titanium (0.018NiTi) (Lot #01H55H).

2) 0.018-inch round stainless steel (0.018ss) (Lot #00M14).

3) 0.019 x 0.025-inch titanium molybdenum alloy (19x25TMA) (Lot #01C12C).

4) 0.018 x 0.025-inch stainless steel (18x25ss) (Lot #01B7B).

5) 0.019 x 0.025-inch stainless steel (19x25ss) (Lot #01B3B).

6) 0.021 x 0.025-inch stainless steel (21x25ss) (Lot #01B5B).

Test Bracket-Acrylic Rod Assembly

A dental surveyor was utilized to mount the test brackets onto the ends of acrylic rods (Figure 7). The acrylic rods were 6 mm in diameter and were cut to 12.6 mm in length. A rectangular acrylic block, with a 6mm diameter hole drilled in its center, was secured to the surveyor table. An acrylic rod was inserted into the hole of the acrylic block. Adhesive (M-Bond 200 Adhesive, M-Line Accessories, Measurements Group, Inc., Raleigh, N.C.) was placed on the mesh pad of the bracket and then it was placed on the acrylic rod surface. The surveyor pin was ground into the shape of a blade, with its width equaling the bracket slot. The pin was then inserted into the bracket slot to align and center the bracket on the acrylic rod surface; therefore, negating the -7^{o} torque prescription in the bracket (Figure 8). Isopropyl alcohol (200 Catalyst-C, M-Line Accessories, Measurements Group, Inc., Raleigh, N.C.) was painted onto the bracket-rod interface to accelerate bonding.

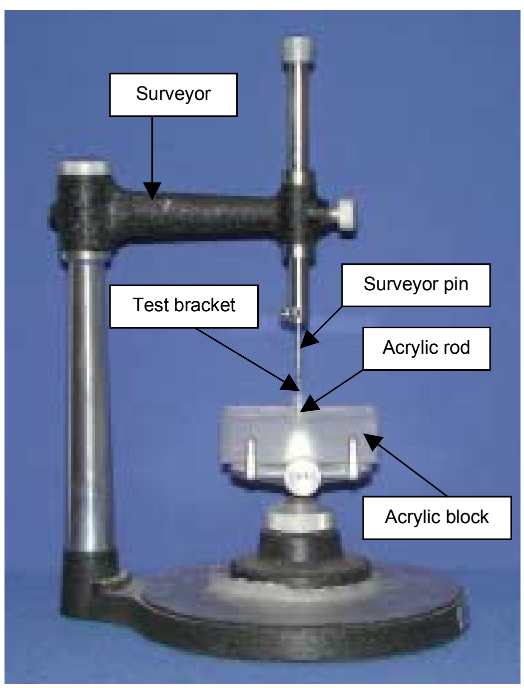

Figure 7. Dental surveyor with acrylic block and acrylic rod utilized to mount test brackets.

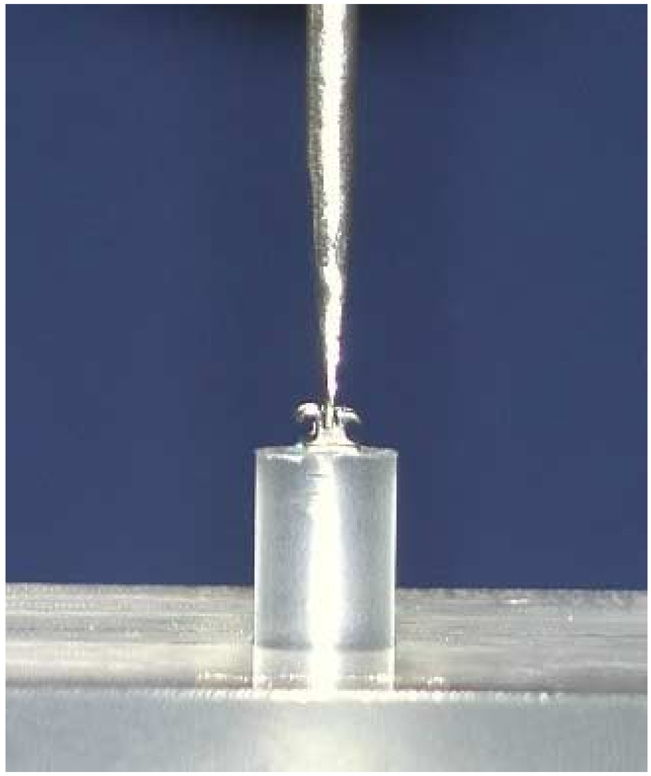

Figure 8. Close-up view of surveyor pin aligning test bracket mounted on acrylic rod.

Pilot Study

A pilot study was conducted to determine:

1) if the apparatus and data collection software were functioning properly
2) if the frictional resistance at the bracket-archwire interface was proportional to the load
3) if the rotating variable moment could be applied and measured
4) if the cyclic rotating variable moment at the bracket-archwire interface influenced friction.

Only Minitwin brackets and 0.018-inch and 0.018 x 0.025-inch stainless steel wires were tested. The data from these trials were included in the results. The information obtained from the pilot study enabled us to replicate results of previous research and to predict the data obtained when the remaining brackets and archwires were studied.

After the pilot study was completed, the remaining brackets and archwires were tested in the following order:

Order of brackets studied:

1) Minitwin
2) Transcend 6000
3) Damon 2
4) In-Ovation

Order of archwires studied:

1) 0.018-inch nickel titanium
2) 0.018-inch stainless steel
3) 0.018 x 0.025-inch stainless steel
4) 0.019 x 0.025-inch titanium molybdenum alloy
5) 0.019 x 0.025-inch stainless steel
6) 0.021 x 0.025-inch stainless steel

The Minitwin bracket was selected due to its popularity and the Transcend 6000 ceramic bracket for its alleged high friction. The Damon 2 and In-Ovation self-ligating brackets were chosen due to their popularity, proposed reduced friction over conventional brackets and their differing mechanisms of archwire engagement. The wires were chosen due to their popularity and frequent use in sliding mechanics.

Apparatus Setup

A mounting plate was fabricated to aid in the alignment of archwires through test bracket slots. The mounting plate was made of acrylic and had a hole drilled through its center, with the diameter being larger than the acrylic rod on which the test bracket is bonded (Figure 9). On either side, from the center of the hole, were Damon 2 maxillary right first premolar brackets, 19.2 mm apart. This distance is the average space between a maxillary canine and second premolar. All brackets were oriented in the same direction, with the distogingival dot positioned superiorly and to the left. This means that all bracket slots were vertically oriented. The mounting plate was secured with screws to the superior end of two upright rectangular metal poles. The opposite end was attached to a platform that rested on the Instron machine. The mounting plate was not changed throughout the entire study, as this may have altered the findings or values due to the possible differences in alignment of the Damon 2 brackets. The metal poles maintained a constant width, yet at its base, allowed for adjustments to be made right or left, to allow for passive wire engagement through the test bracket slot. The platform could also be moved forward and backward to further aid in passive wire engagement in the bracket slot.

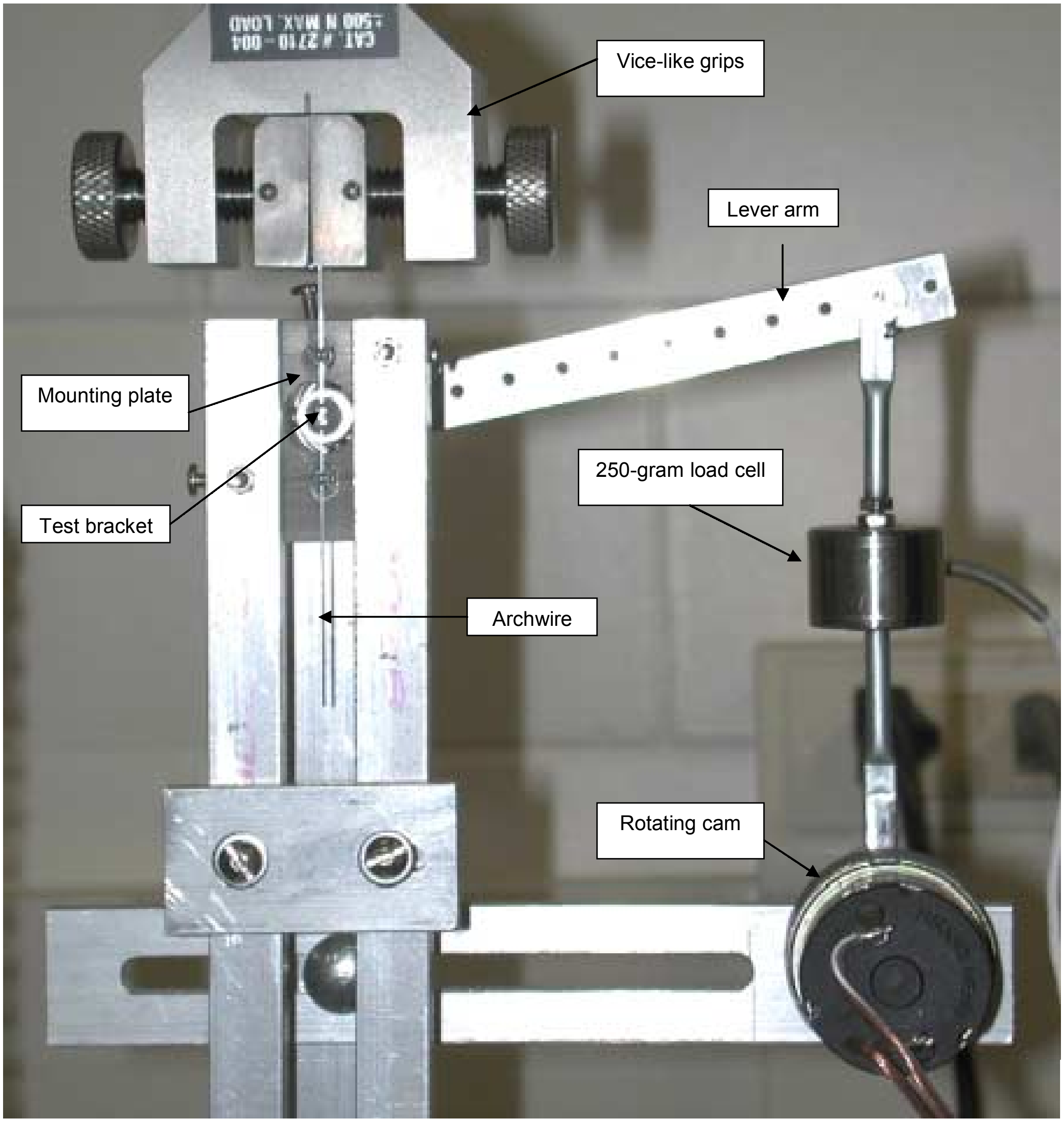

Figure 9. Photograph showing main part of the apparatus consisting of vice-like grips, mounting plate, test bracket, archwire, lever arm, 250-gram load cell and rotating cam.

Test Bracket-Archwire Alignment

The test bracket-rod assembly was inserted through the hole in the mounting plate. The test bracket was passed through the template hole and then an archwire was inserted through all three bracket slots in a vertical manner (Figure 10). Prior to each trial, the test bracket and archwire were wiped with alcohol to remove any residue and then air-dried. The bracket-rod assembly could be rotated clockwise, counter-clockwise, in and out to aid in further passive archwire engagement in the bracket slot; therefore, negating the 2^{o} tip in the Damon 2 and In-Ovation brackets. Once the proper alignment was achieved, the bracket-rod assembly, which was attached to the lever arm, was secured to prevent any additional movement.

At this time, an elastomeric tie (Ormco, Power O Mini-Stik, 0.120, Item #640-1265, Lot #8J3) was ligated around the Minitwin or Transcend 6000 brackets or the gates of the Damon 2 and In-Ovation brackets were closed. The vice-like grips of the Instron machine engaged 5 mm of the archwire, and the distance from the vice-like grips to the center of the test bracket was measured at 25 mm. Since the Instron machine pulled the archwire superiorly through the bracket slots, the distance between the vice-like grips and center of the test bracket were brought down to less than 25 mm, and then returned to 25 mm to allow the entire apparatus, especially the forces between the archwire and elastomeric ties, to be pulled in the same direction as the archwire. Before the trial commenced, the vice-like grips were once again released from the archwire and then re-engaged to ensure passivity.

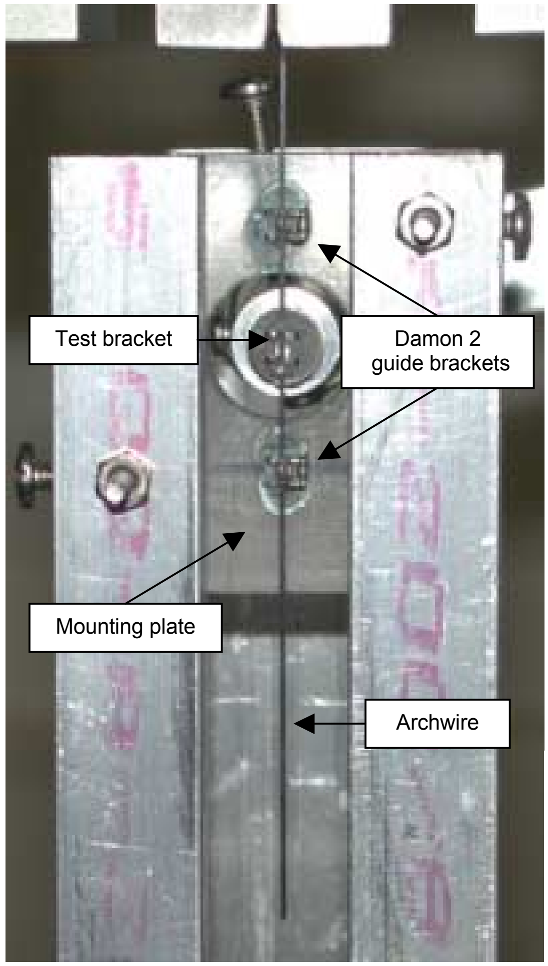

Figure 10. Close-up view of archwire alignment through Damon 2 brackets, on mounting plate, and test bracket.

All archwires used in this study, except the 0.018-inch nickel titanium, were cut to 80 mm straight pieces. The 0.018-inch nickel titanium archwires were cut to a length of 50 mm from a maxillary large broad archform; therefore, resulting in a slight curve present at one end. This is due to the fact that nickel titanium archwires were not available in straight pieces. In this study, the curve of the nickel titanium archwire was consistently directed toward the back of the testing machine.

Load Cells and Computer Setup

Prior to data collection, a 50-gram weight was used to calibrate the 250-gram load cell (Sensotec, Inc. Model 31/1435-03). This load cell measured the load required to tip the bracket/archwire to an angulation of 20^o. It was interfaced with a custom built computer containing an Intel Celeron processor and Labtech software (Laboratory Technologies Corporation © 1999, Labtech Control Version 11, Universal) recording all the data. It was attached superiorly to the lever arm and inferiorly to the rotating cam, which created the variable moments. The load cell was attached to the lever arm at a distance of 10 cm from the lever arm's center of rotation, which was directly behind the test bracket-rod assembly. The lever arm movement was measured, with a protractor, to have an oscillation range of 20^o due to the rotating cam.

The second load cell, ±1 kN (Instron, UK 598) located on top of the Instron machine, was calibrated with a 1000-gram weight. This load cell recorded the friction at the bracket-archwire interface. This load cell was also interfaced with the same custom built computer utilizing the Labtech software as the 250-gram load cell. A Gateway E3000 system containing Merlin software (Instron Merlin Program, Version 3.23) controlled the crosshead speed of the archwire (5mm/min).

DC Power Supply

A DC Power Supply (Maxtel International Corporation, BK Precision, Triple Output DC Power Supply 1651) was connected to the rotating cam that oscillated the lever arm to produce the variable moments. It was set at 11 volts, which correlated to 1 Hertz or 60 cycles/minute (Figure 11). This simulated the chewing frequency in humans.

As the rotating cam moved cyclically, the measured load would change correspondingly. When the cam was rotated to its highest vertical dimension, the minimum load was applied. Conversely, when the cam was rotated to its smallest vertical dimension, the maximum load was applied. The connection of the lever arm to the rotating cam was positioned to vary the load from zero to the resulting maximum. Before the archwire was engaged in the test bracket, the rotating cam was turned until the 250-gram load cell was at its most superior position (i.e. at 12 o'clock), the minimum load.

Bridge Amplifiers

Two bridge amplifiers were used in this study to provide excitation for the load cells and to amplify the signal voltage (proportional to load) (Fig 11). The Signal Conditioning Amplifier (Measurements Group, Instruments Division, Model 2311) attached to the ±1 kN load cell, to measure friction, was reset to zero prior to each trial. The second amplifier (Sensotec, Inc., Signal Conditioner-Indicator, Model GM), used to measure load and connected to the 250-gram load cell, was not reset to zero prior to each trial. Instead, with the load data transferred into Microsoft Excel 2000, the first 10 seconds was averaged and this value was then subtracted from all the load data to compensate for offset and any noise present, with no crosshead movement, within the apparatus. The subtracted load data was then multiplied by 10, due to the 10 cm lever arm length, to obtain the true moment.

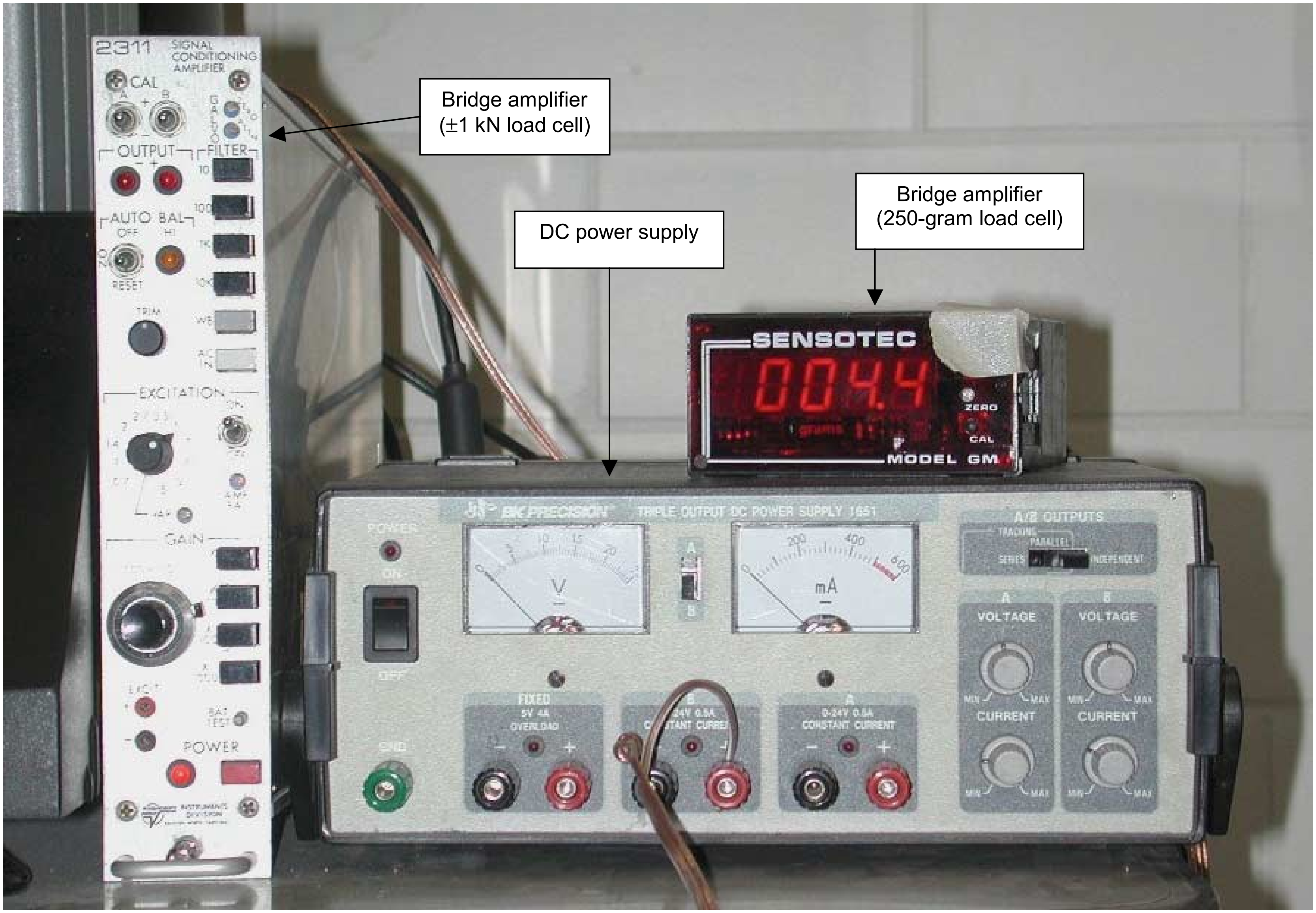

Figure 11. DC power supply and two bridge amplifiers.

Test Trial Intervals

Each trial was 60 seconds in length and the intervals are provided below:

0-10 seconds	noise /offset (no archwire pull and no variable moments)
10 seconds	begin archwire pull at a crosshead speed of 5 mm/min for 40 seconds
20 seconds	rotating cam turned on to produce variable moments for 40 seconds
50 seconds	archwire pull stopped; cam rotation continued
60 seconds	rotating cam turned off; data collection completed

After each trial, the archwire and test bracket-rod assembly were removed and replaced with new ones.

Trials were also performed with the absence of a test bracket while an archwire was inserted in the slots of the two guide Damon 2 brackets on the mounting plate. This was tested to measure the amount of load and friction caused by the Damon 2 guide brackets and the test apparatus.

Data Collection and Evaluation

As stated above, all data was collected (DC voltages) and scaled by the computer using Labtech software. Each bracket-archwire combination was tested 5 times; therefore, a total of 120 trials were performed. Measurements were taken every tenth of a second (0.10 seconds/measurement) for 60 seconds for both load and friction values. Load was in units of gram-centimeters, due to the lever arm length, while friction was in units of grams. The raw data was transferred to Microsoft Excel 2000, where the appropriate titles for archwires, brackets and trial number were placed. Headings for each of the 4 columns (time, load, friction, trigger) were also assigned. As stated earlier, the first 10 seconds of the load data was averaged and this value was then subtracted from all the load data and multiplied by 10 to obtain the true load. This was necessary because the amplifier connected to the 250-gram load cell recording the load data was not reset to zero prior to each trial. However, the friction data was not adjusted because the amplifier connected to the ± 1 kN load cell used to measure friction was reset to zero prior to each trial. An example is shown below (Table 1).

Table 1. Sample data obtained from test trials.

0.018 x 0.025-inch stainless steel, Minitwin, Trial #1					
Time (seconds)	**Load (gm-cm)**	**Friction (gm)**	**Trigger**	**True Load (gm-cm)**	**Avg**
12.0	2.189	127.275	-0.005	2.792	1.909
12.1	1.702	127.275	0.000	-2.072	
12.2	2.189	127.275	0.000	2.792	
12.3	1.702	131.821	0.000	-2.072	
12.4	1.945	131.821	-0.005	0.360	
12.5	1.945	131.821	-0.005	0.360	

Data from every trial was graphed using Microsoft Excel 2000. Two y-axes were placed on each graph. Friction (gm) was on the left y-axes and Load (gm-cm) was on the right y-axes. The x-axis was labeled Time (seconds). An example is shown below in Figure 12.

A visual average for the maximum and minimum dynamic friction, apparent stiffness and dynamic load values were obtained from each graph plotted for each bracket-archwire combination. These numbers were then input into Microsoft Excel 2000 to obtain the average dynamic friction, apparent stiffness and dynamic load.

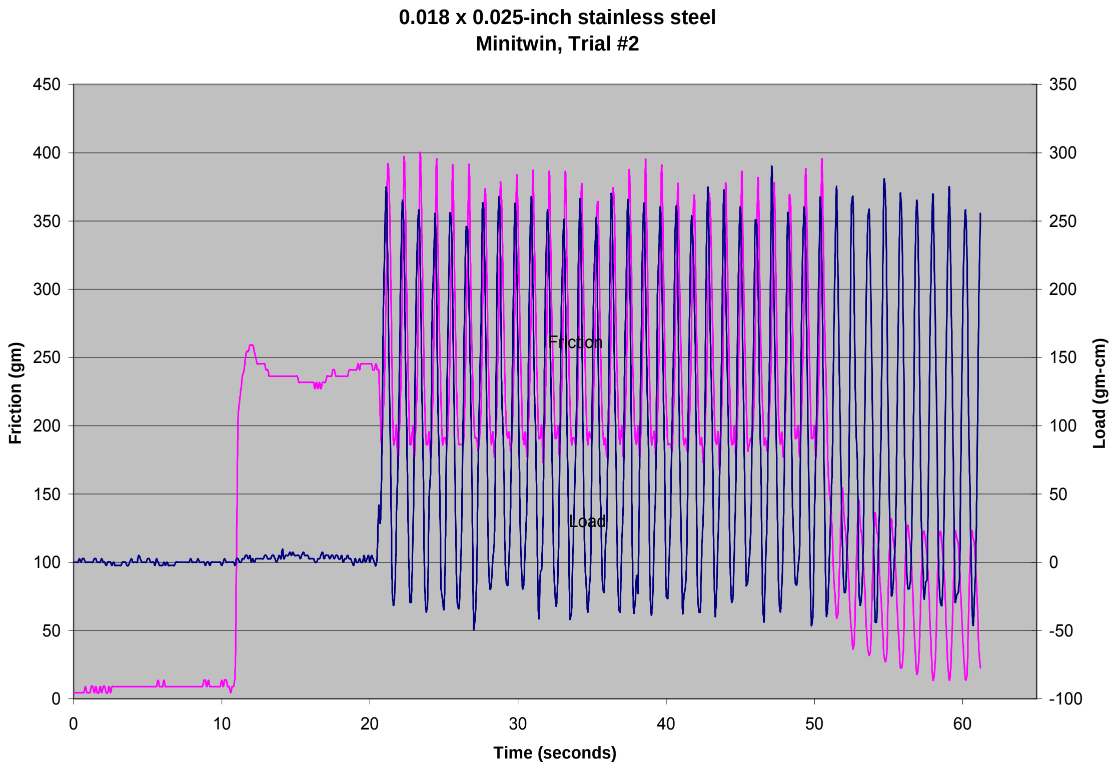

Figure 12. Sample graph of raw data.

Static and kinetic friction was obtained directly from the data. Bracket-archwire combinations were averaged for each type of friction. Static friction was the point where the friction increased at about 10 seconds to its maximum value. Kinetic friction was the average of the range from 13-17 seconds.

Archwire Dimension(s) and Bracket Slot Measurements

Bracket slot lengths were measured for all brackets used in the study. A digital caliper was placed on the mesial and distal ends of the bracket slot. An average slot length was obtained for each bracket. A digital caliper was also used to measure the archwire dimension(s) for all archwires used in this study. Once again, an average archwire dimension was calculated.

Data Analysis

Data was analyzed to compare:

1) static, kinetic and dynamic friction
2) dynamic friction and dynamic load
3) dynamic load and apparent stiffness
4) bracket slot lengths
5) archwire sizes
6) contact angles

Statistics

JMP version 3.1.5 statistical analysis software was used to calculate ANOVA ($p<0.0001$) and Tukey-Kramer Honest Significant Difference (HSD) ($p<0.05$). Microsoft Excel 2000 was used to calculate the average and standard deviation.

Wire Stiffness Chart

A wire stiffness chart was provided by Ormco. It was used to analyze the results obtained from this study. A portion of the chart is provided below in Table 2. Due to the vertical orientation of the bracket slot, the variable moments placed at the bracket-archwire interface were rotated about side 2. Therefore, the side 2 wire stiffness numbers were used for comparison.

Table 2. A portion of the wire stiffness chart provided by Ormco.

Archwire	Ms	Wire Stiffness Side 1	Wire Stiffness Side 2
0.018NiTi	0.12	49	
0.018ss	1.00	410	
19x25TMA	0.40	787	455
18x25ss	1.00	1865	967
19x25ss	1.00	1968	1137
21x25ss	1.00	2175	1535

Ms = relative modulus of elasticity, with stainless steel equaling 1.00.

Side 1 = the larger dimension of a rectangular wire, for example 0.025" in a 0.019" x 0.025" wire, which is the buccal-lingual dimension.

Side 2 = the smaller dimension of a rectangular wire, for example 0.019" in a 0.019" x 0.025" wire, which is against the back of the bracket slot.

Contact Angle

The contact angle[133] for each bracket-archwire combination was calculated using the average archwire dimension(s) and bracket slot lengths obtained from this study.

$$\text{Contact Angle } (\theta_c) = \frac{57.3\,[1-(\text{size/slot})]}{(\text{width/slot})}$$

size = the archwire dimension that contacts the floor of the slot

slot = the bracket dimension at the floor of the slot

width = the mesial-distal dimension of the bracket

CHAPTER 4

RESULTS

Introduction

Three types of friction were investigated in this study (Figure 13). Static friction is the smallest force needed to start the motion of solid surfaces that were previously at rest with respect to each other. On the graph, it was the point where the friction increased at about 10 seconds to its maximum value. Kinetic friction is the force that resists the sliding motion of one solid object over another at a constant speed. On this graph it was the average of the friction range from 13-17 seconds. Dynamic friction is defined in this study as the frictional force that occurs when the applied (normal) force is variable (dynamic load). In Figure 13, it was the average of the friction from about 20-50 seconds. Friction results were summarized in Table 3.

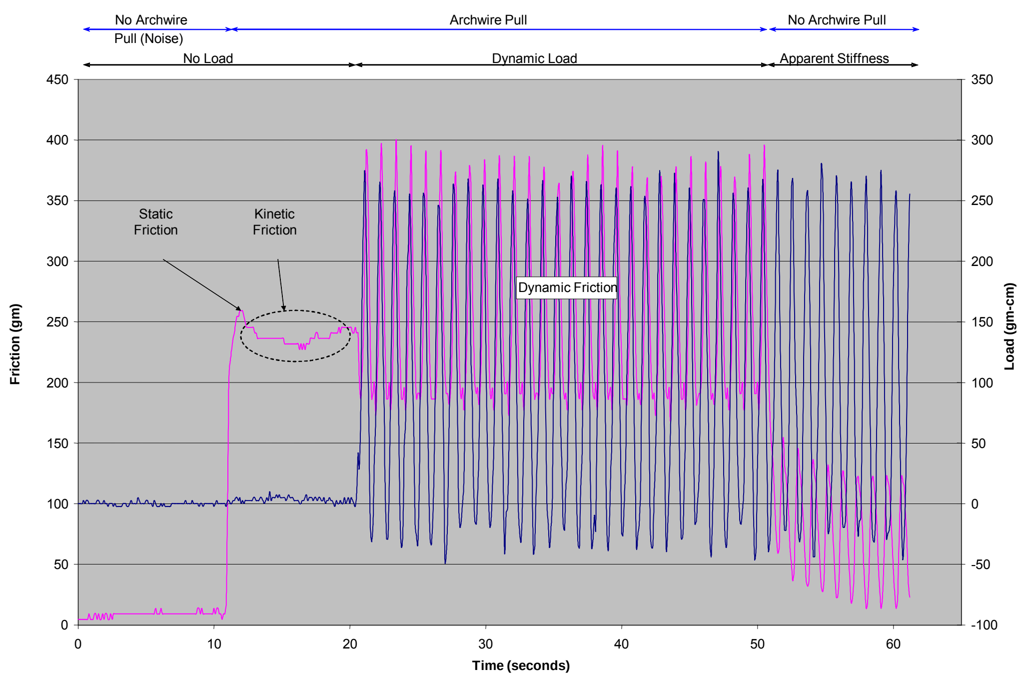

Figure 13. Sample graph of raw data with labels.

Two types of load were investigated. Dynamic load was the variable tipping (0-20^{o}) force occurring with archwire pull. In this graph, it was the average of the load from about 20-50 seconds. Apparent stiffness is the force (stiffness) measured with variable tipping but without archwire pull. In Figure 13, it was the average of the load from 50-60 seconds.

The first 10 seconds of each trial measured the noise present within the system. The Instron machine pulled the archwire from 11-50 seconds. The rotating cam was turned on from 21-60 seconds.

A 3-way analysis of variance (ANOVA), with 4 terms, was used to compare three factors (friction type, archwire and bracket) and one interaction term (bracket-archwire). The results revealed that the friction type, archwire, bracket, and bracket-archwire interactions were all statistically significant at an alpha level of < 0.0001.

In general, static and kinetic friction were similar, while dynamic friction was statistically higher. Minitwin and Transcend 6000 conventional brackets produced greater friction than In-Ovation and Damon 2 self-ligating brackets, except with 19x25TMA. In general, the Damon 2 bracket produced the least amount of friction while the Minitwin and Transcend 6000 brackets produced the greatest amount of friction. Both the 0.018NiTi and 0.018ss archwires yielded the least friction while the 21x25ss archwire produced the greatest friction.

Table 3. Static, kinetic and dynamic friction with standard deviation for each bracket-archwire combination.

Bracket	Archwire	Static Friction (gm)	Kinetic Friction (gm)	Dynamic Friction (gm)
Minitwin	0.018NiTi	188 ± 83	185 ± 77	205 ± 60
	0.018ss	145 ± 70	131 ± 63	150 ± 48
	19x25TMA	134 ± 68	117 ± 60	184 ± 74
	18x25ss	185 ± 60	177 ± 54	232 ± 79
	19x25ss	240 ± 48	226 ± 41	379 ± 72
	21x25ss	649 ± 247	651 ± 252	693 ± 124
Transcend 6000	0.018NiTi	234 ± 19	222 ± 21	254 ± 30
	0.018ss	89 ± 18	80 ± 14	155 ± 28
	19x25TMA	142 ± 68	146 ± 56	230 ± 55
	18x25ss	235 ± 122	225 ± 116	280 ± 76
	19x25ss	298 ± 45	292 ± 34	455 ± 28
	21x25ss	442 ± 128	460 ± 142	702 ± 178
In-Ovation	0.018NiTi	4 ± 2	1 ± 1	5 ± 2
	0.018ss	0	-1	32 ± 18
	19x25TMA	296 ± 49	279 ± 50	305 ± 57
	18x25ss	183 ± 89	178 ± 84	134 ± 22
	19x25ss	136 ± 36	139 ± 35	238 ± 74
	21x25ss	296 ± 116	304 ± 118	399 ± 63
Damon 2	0.018NiTi	7 ± 4	5 ± 4	18 ± 9
	0.018ss	4 ± 5	0	22 ± 3
	19x25TMA	212 ± 76	181 ± 56	209 ± 56
	18x25ss	32 ± 11	30 ± 10	62 ± 27
	19x25ss	20 ± 12	18 ± 13	99 ± 41
	21x25ss	172 ± 20	176 ± 21	259 ± 23

Friction Types

When all brackets and archwires were combined for analysis, the Tukey-Kramer HSD analysis, at an alpha level of 0.05, revealed that the static friction (181 gm) and kinetic friction (176 gm) were not statistically significant. Dynamic friction (237 gm) was statistically different from static friction and kinetic friction (Figure 14). Bar graphs of the 4 brackets with static, kinetic and dynamic friction for each of the 6 archwires are shown in Figures 15 to 18. The figures demonstrate similar friction results. Although static and kinetic friction were not statistically significant, 18 of the 24 bracket-archwire combinations resulted in average static friction (181 gm) being larger than average kinetic friction (176 gm). Average dynamic friction (237 gm) was greater than average kinetic friction in 23 of the 24 bracket-archwire combinations.

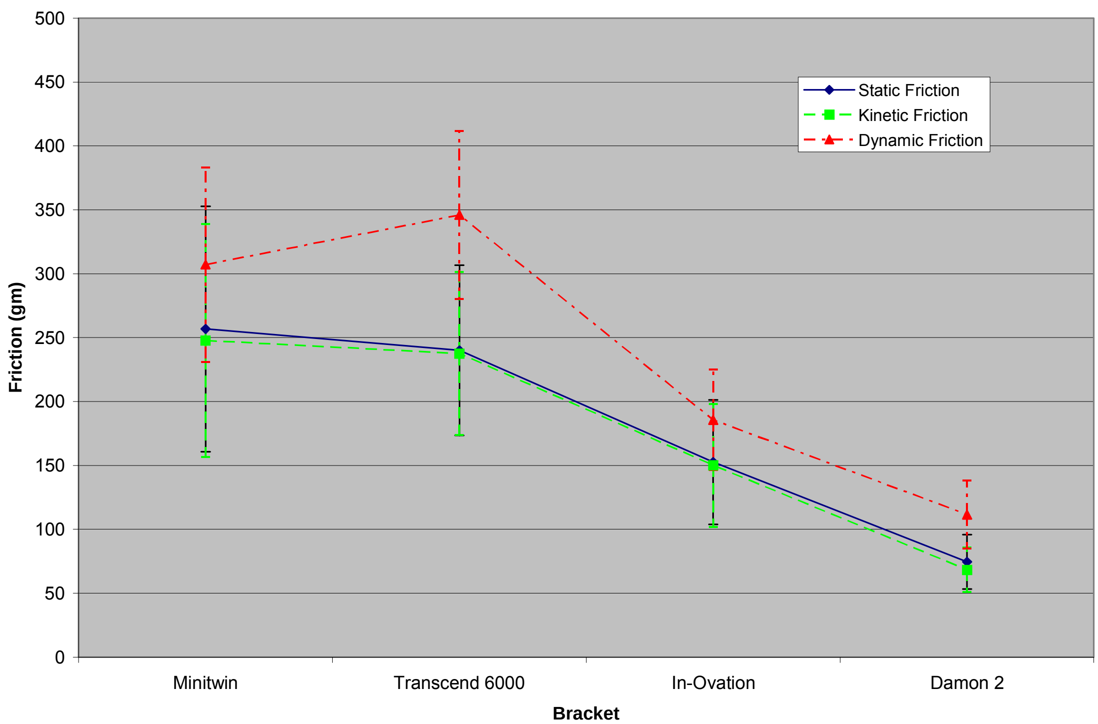

Figure 14. An average of the static, kinetic and dynamic friction with the standard deviation of all wires for each bracket was calculated. The line graph shows the similarity between static friction and kinetic friction, while dynamic friction was statistically significant.

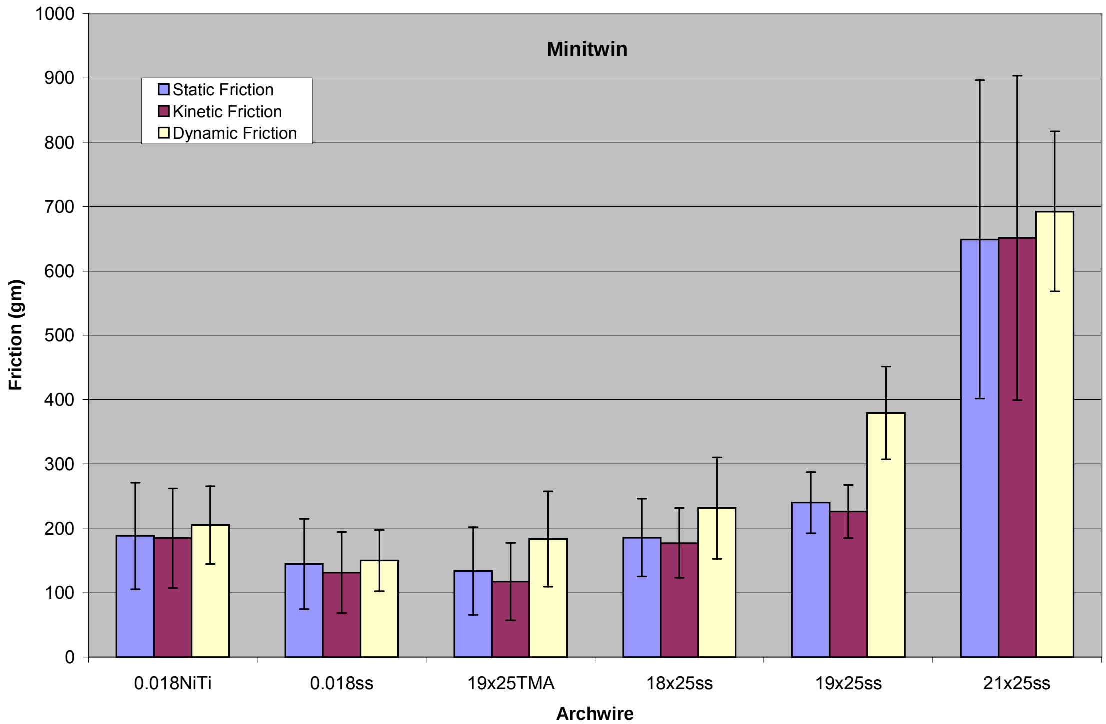

Figure 15. Bar graph with the standard deviation of friction type for the Minitwin bracket grouped by archwires.

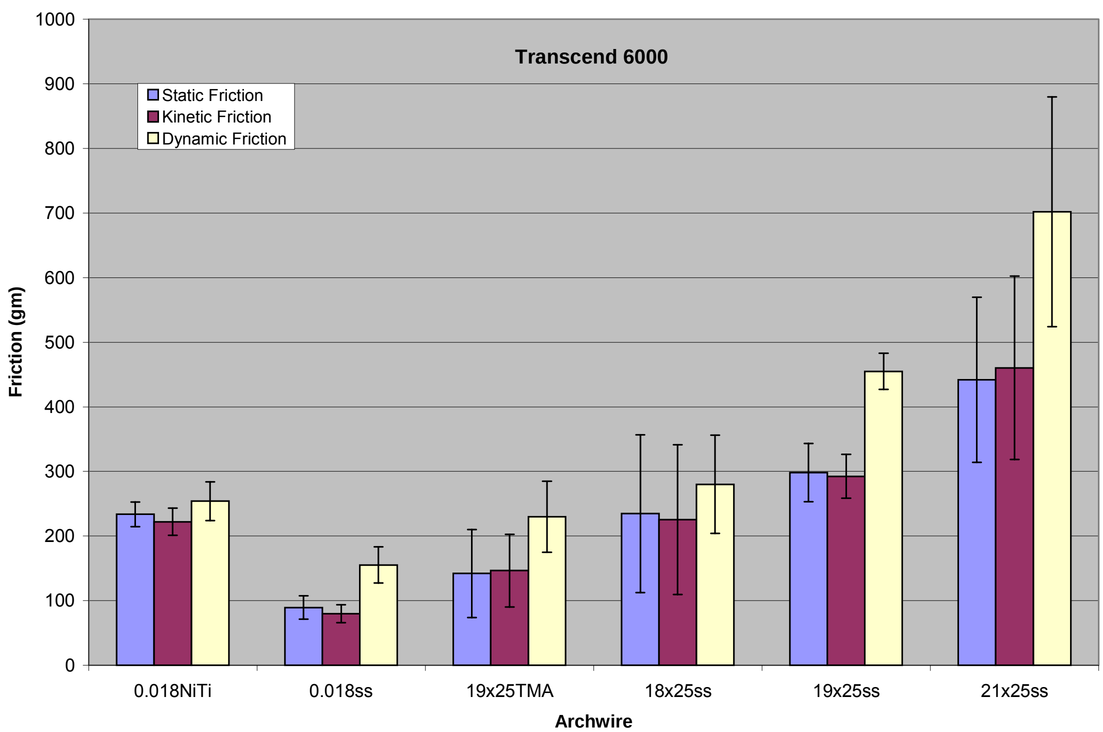

Figure 16. Bar graph with the standard deviation of friction type for the Transcend 6000 bracket grouped by archwires.

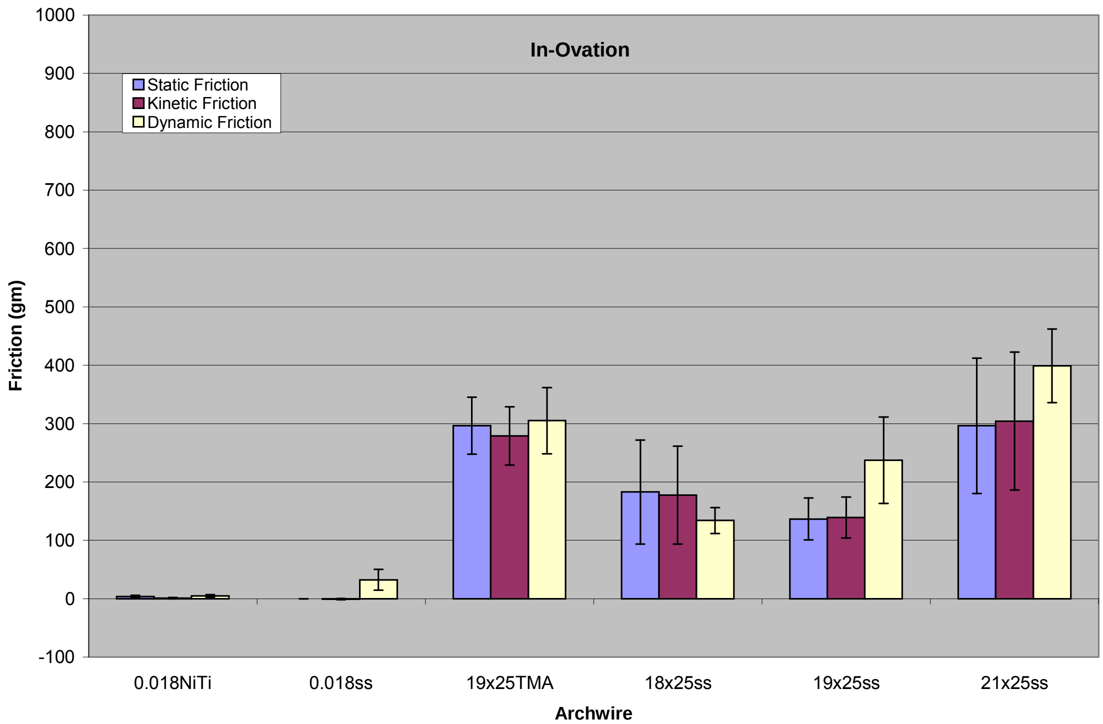

Figure 17. Bar graph with the standard deviation of friction type for the In-Ovation bracket grouped by archwires.

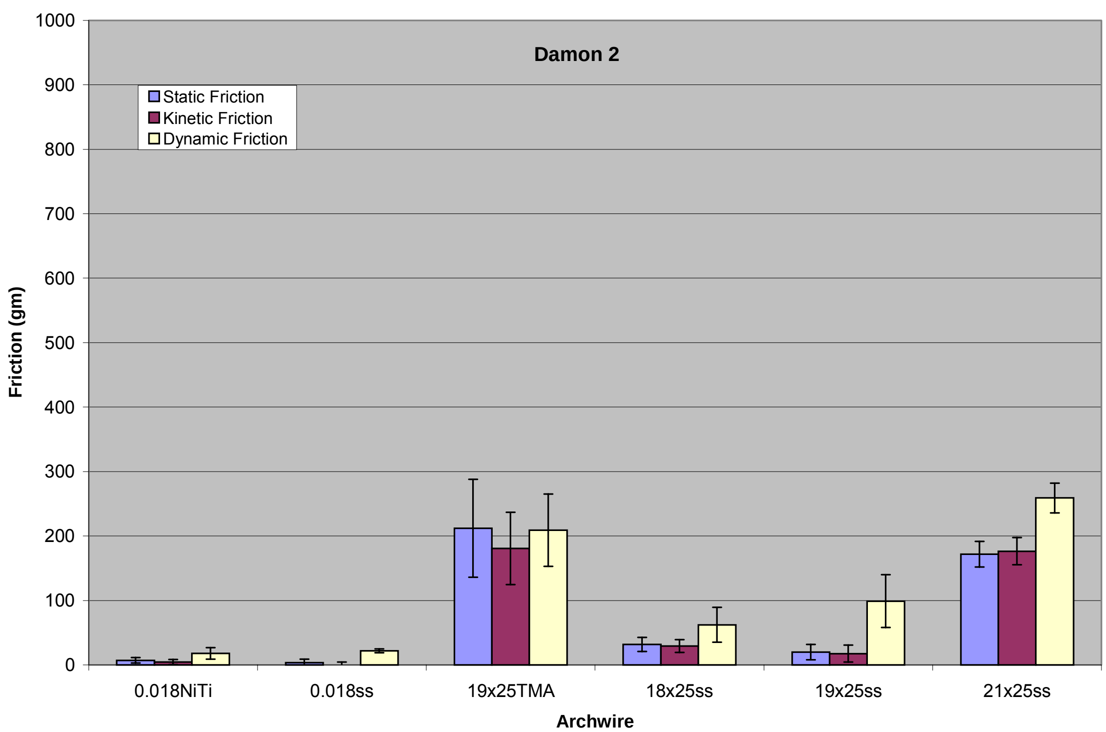

Figure 18. Bar graph with the standard deviation of friction type for the Damon 2 bracket grouped by archwires.

Archwires

The Tukey-Kramer HSD analysis, with an alpha level of 0.05, was used to analyze the archwires. No archwires were permanently deformed in any of the trials. When the 3 friction types and 4 brackets were averaged for each archwire, a line graph revealed the following order of friction from low to high with the averages in parentheses: 0.018ss (67 gm), 0.018NiTi (111 gm), 18x25ss (163 gm), 19x25TMA (203 gm), 19x25ss (212 gm), 21x25ss (434 gm) (Figure 19).

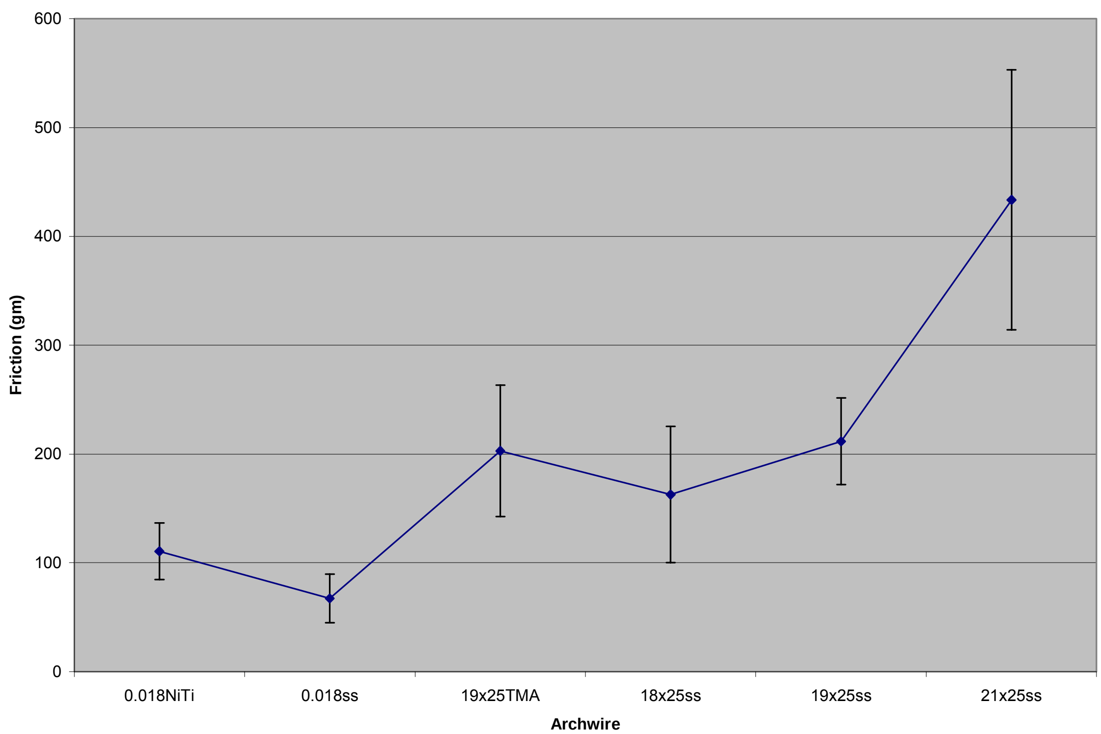

Figure 19. The static, kinetic and dynamic friction with the standard deviation of the 4 brackets were averaged to obtain the friction for each archwire.

The following groups of archwires were found to be similar (Figure 20): Group 1 - 0.018ss and 0.018NiTi; Group 2 - 0.018NiTi and 18x25ss; Group 3 - 18x25ss, 19x25TMA and 19x25ss. The 21x25ss archwire was statistically different from all other archwires.

0.018ss 0.018NiTi 18x25ss 19x25TMA 19x25ss 21x25ss

Figure 20. Archwire groups. Lines beneath wires indicate no statistical significance.

The 0.018ss and 0.018NiTi were not statistically different despite their different composition and stiffness. The 18x25ss, 19x25TMA and 19x25ss were grouped together despite their differing archwire dimensions and compositions. Despite these differences, all 3 archwires produced friction amounts that were not statistically different.

<u>Brackets</u>

When friction type and archwires were combined, the Tukey-Kramer HSD analysis, at an alpha level of 0.05, found the Minitwin (271 gm) and Transcend 6000 (275 gm) brackets not to be statistically different. In-Ovation (163 gm) and Damon 2 (85 gm) brackets yielded statistically different amounts of friction when compared to each other, and to the Minitwin and Transcend 6000 brackets (Figure 21 and Figure 22).

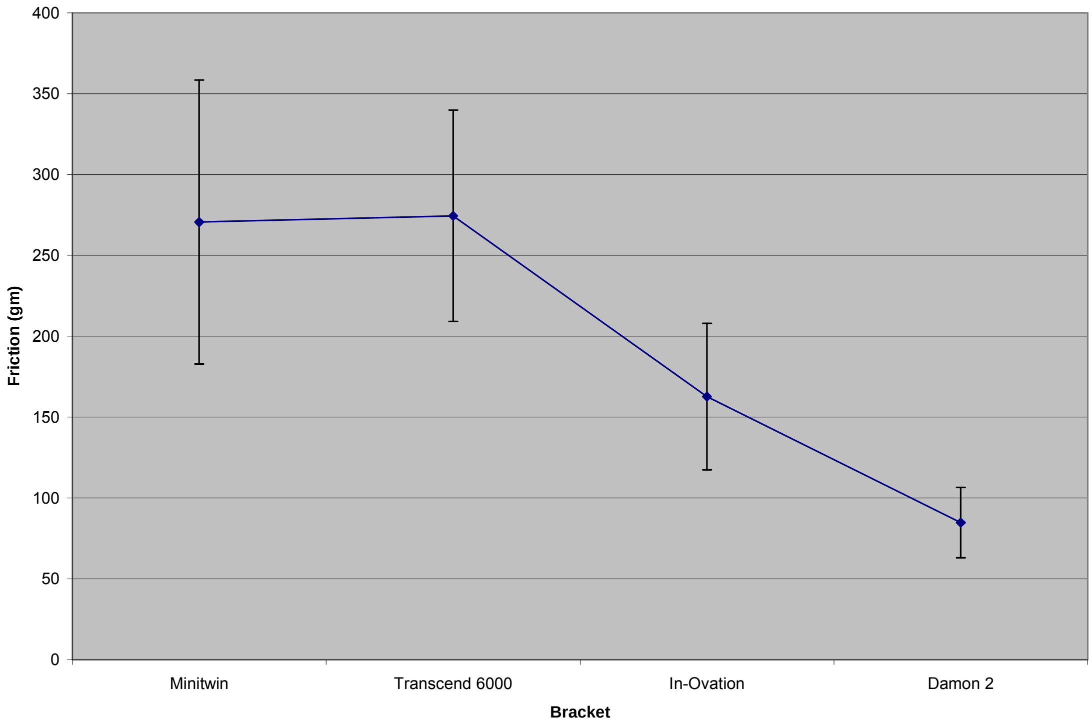

Figure 21. The static, kinetic and dynamic friction with the standard deviation of the 6 archwires were averaged to obtain the friction for each bracket.

Minitwin	Transcend 6000	In-Ovation	Damon 2

Figure 22. Bracket groupings. Line under Minitwin and Transcend 6000 indicate no statistical significance.

Bracket-Archwire Interactions

In general, the conventional brackets and self-ligating brackets formed two distinct groups for the 0.018NiTi and 0.018ss, as shown in Figure 23 and Figure 24. There were complex bracket-archwire interactions for the 19x25TMA and 18x25ss archwires. An average for the static and kinetic frictions for each bracket-archwire combination was calculated (Figure 23), since the Tukey-Kramer HSD analysis revealed that their frictions were not statistically significant.

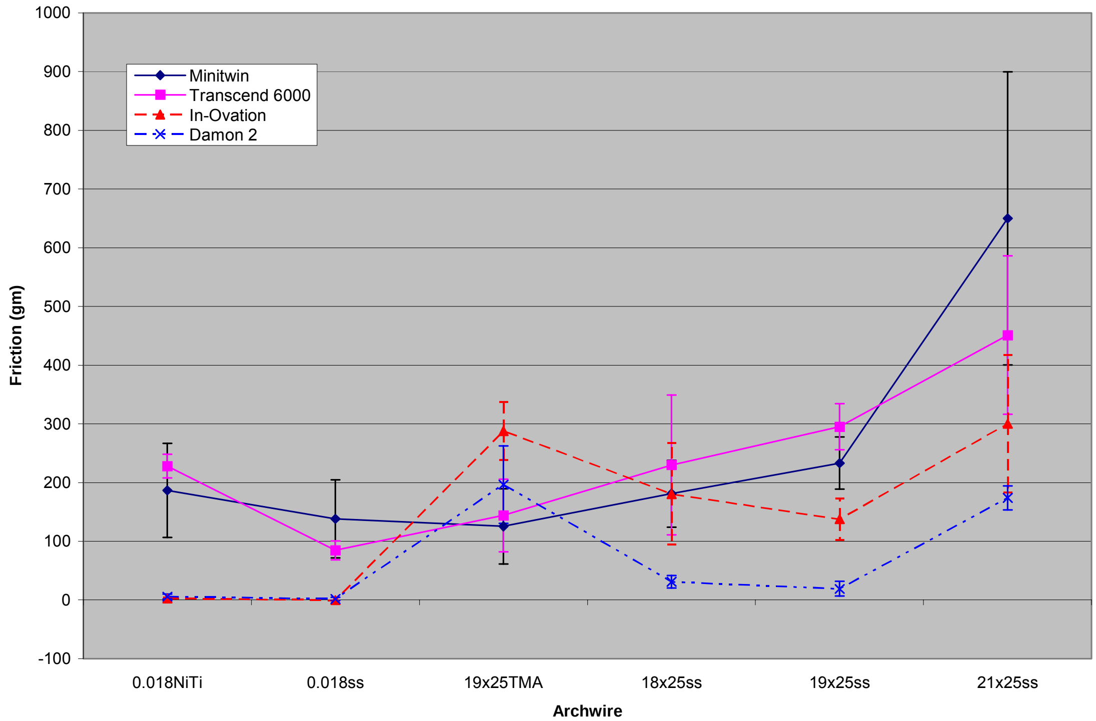

Figure 23. Static and kinetic friction averaged with the standard deviation for each bracket-archwire combination.

The graph revealed that Minitwin and Transcend 6000 brackets produced greater friction than In-Ovation and Damon 2 brackets, except with the 19x25TMA archwire. As stated previously, Minitwin and Transcend 6000 brackets were similar while In-Ovation and Damon 2 brackets were statistically significant from one another depending on the archwire. The In-Ovation and Damon 2 brackets had a similar amount of friction, and less than that of the Minitwin and Transcend 6000 brackets, with the 0.018NiTi and 0.018ss. The In-Ovation and Damon 2 brackets had different amounts of friction for the remaining 4 archwires.

Dynamic friction was graphed for each bracket-archwire combination (Figure 24).

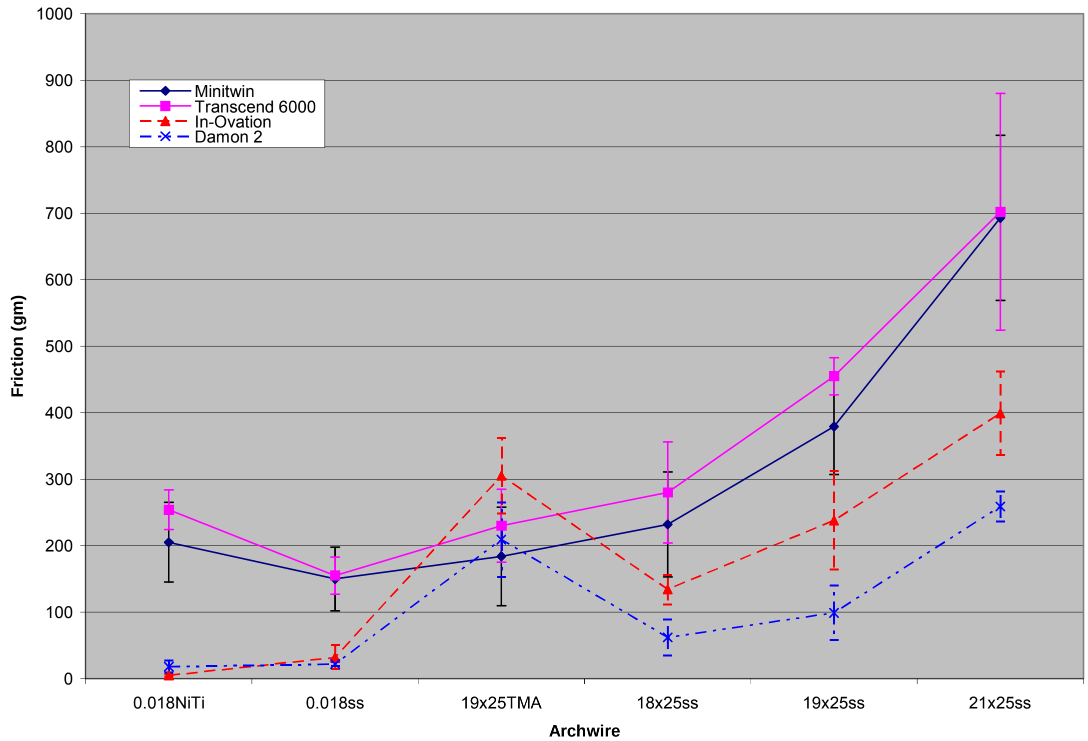

Figure 24. Dynamic friction with the standard deviation for each bracket-archwire combination.

This graph is very similar to the graph in Figure 23. The Minitwin and Transcend 6000 brackets produced greater friction than the In-Ovation and Damon 2 brackets, except with the 19x25TMA archwire. There were two notable differences between the two graphs: 1) with the 19x25TMA archwire, the Transcend 6000 bracket produced greater friction than the Damon 2 bracket 2) with the 18x25ss archwire, the Minitwin bracket produced greater friction than the In-Ovation bracket. The previous graph revealed an equal amount of friction for the two brackets.

<u>Dynamic Load vs Dynamic Friction</u>

The graph in Figure 25 shows that the dynamic load is proportional to the dynamic friction. The R-value of 0.62 was statistically significant at $p<0.0001$. In other words, the R-value indicated how much of the dynamic friction variability was predicted by the variability of the dynamic load.

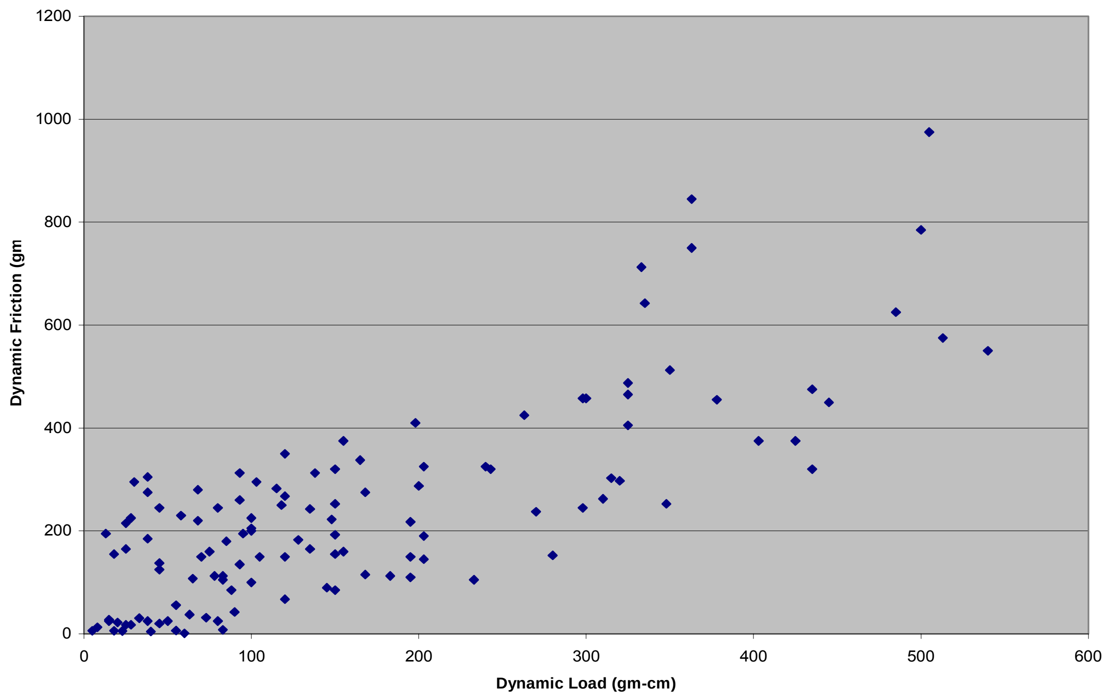

Figure 25. Dynamic load is proportional to dynamic friction.

<u>Bracket Slot Length</u>

Bracket slot length of each bracket was measured using a digital caliper (Table 4). These measurements were used to calculate the contact angles. All test brackets were measured and then an average for each bracket was calculated. The Transcend 6000 bracket had the longest bracket slot at 3.51 mm while the Damon 2 bracket had the shortest at 2.67 mm.

Table 4. Table comparing average bracket slot lengths with the standard deviation.

	Minitwin	Transcend 6000	Damon 2	In-Ovation
Millimeters	2.81 ± 0.02	3.51 ± 0.01	2.67 ± 0.01	3.18 ± 0.01

Archwire Dimension

Archwire dimension was also measured using a digital caliper (Table 5). All archwires were measured and then an average for each archwire was calculated. This measurement was used to calculate the contact angle. Side 1 (incisal-gingival) is the smaller dimension of a rectangular archwire, while Side 2 (facial-lingual) is the larger dimension.

Table 5. Table comparing average archwire dimensions with the standard deviation. * indicates standard deviation <0.0001.

Archwire	Inches Side 1	Inches Side 2
0.018NiTi	0.018*	
0.018ss	0.018*	
19x25TMA	0.019*	0.024 ± 0.0002
18x25ss	0.018 ± 0.0002	0.025 ± 0.0002
19x25ss	0.019*	0.024*
21x25ss	0.021*	0.025 ± 0.0002

The 0.018NiTi, 0.018ss, 18x25ss and 21x25ss archwires had the specified manufacturer dimensions, whereas Side 2 of the 19x25TMA and 19x25ss archwires were smaller by 0.001-inch.

Contact Angle

The contact angle for each bracket-archwire combination was calculated. This was compared to the mean apparent stiffness to determine if a relationship existed. The largest difference in contact angle, with the same archwire, was 0.5^{o} between the Transcend 6000 and Damon 2 brackets. The total range of the variable tipping was 20^{o}.

When compared to the 20^{o} tip, the contact angle difference of 0.5^{o} is considered not clinically relevant (Table 6).

Table 6. Table comparing contact angle to mean apparent stiffness.

Archwire	Minitwin (degrees)	Transcend 6000 (degrees)	Damon 2 (degrees)	In-Ovation (degrees)	Mean Apparent Stiffness (gm-cm ± S.D.)
0.018NiTi	2.2	1.8	2.3	2.0	31 ± 12
0.018ss	2.2	1.8	2.3	2.0	66 ± 24
19x25TMA	1.6	1.3	1.7	1.4	113 ± 19
18x25ss	2.2	1.7	2.3	1.9	131 ± 37
19x25ss	1.6	1.3	1.7	1.4	244 ± 55
21x25ss	0.6	0.5	0.6	0.5	399 ± 20

Apparent Stiffness

During the last 10 seconds of each trial, the variable tipping continued without crosshead movement of the archwire. This evaluated the amount of force needed to rotate the bracket 20^{o}, without archwire pull, for each bracket-archwire combination. This study concluded there was no significant difference between dynamic load and mean apparent stiffness (Table 7).

The apparent stiffness values obtained for each archwire, with all 4 brackets, were averaged. These values were then compared to the wire stiffness chart provided by Ormco to determine if a relationship existed (Table 8). Ms is the relative modulus of elasticity, with stainless steel equaling 1.00. Side 2 is the smaller dimension of a rectangular wire (i.e. 0.019-inch in a 0.019 x 0.025-inch archwire).

Table 7. Table comparing dynamic load vs. apparent stiffness.

Bracket	Archwire	Dynamic Load (gm-cm)	Mean Apparent Stiffness (gm-cm ± S.D.)
Minitwin	0.018NiTi	28 ± 10	29 ± 9
	0.018ss	63 ± 35	61 ± 34
	19x25TMA	95 ± 15	90 ± 11
	18x25ss	109 ± 24	108 ± 24
	19x25ss	265 ± 42	266 ± 48
	21x25ss	351 ± 13	349 ± 14
Transcend 6000	0.018NiTi	41 ± 12	40 ± 12
	0.018ss	99 ± 29	97 ± 25
	19x25TMA	142 ± 23	141 ± 24
	18x25ss	147 ± 39	144 ± 41
	19x25ss	308 ± 67	305 ± 66
	21x25ss	517 ± 24	509 ± 20
In-Ovation	0.018NiTi	42 ± 24	39 ± 19
	0.018ss	68 ± 21	68 ± 24
	19x25TMA	149 ± 19	145 ± 19
	18x25ss	173 ± 53	172 ± 49
	19x25ss	250 ± 50	247 ± 51
	21x25ss	434 ± 19	429 ± 16
Damon 2	0.018NiTi	15 ± 9	14 ± 9
	0.018ss	37 ± 13	36 ± 13
	19x25TMA	78 ± 22	75 ± 23
	18x25ss	99 ± 33	98 ± 34
	19x25ss	160 ± 56	157 ± 56
	21x25ss	305 ± 29	302 ± 41

Table 8. Table comparing wire stiffness to mean apparent stiffness. Ms is the relative modulus of elasticity, with stainless steel equaling 1.00. Side 2 is the smaller dimension of a rectangular archwire.

Archwire	Ms	Wire Stiffness Side 2	Mean Apparent Stiffness (gm-cm ± S.D.)
0.018NiTi	0.12	49	31
0.018ss	1.00	410	66
19x25TMA	0.40	455	113
18x25ss	1.00	967	131
19x25ss	1.00	1137	244
21x25ss	1.00	1535	399

The results revealed that mean apparent stiffness was statistically correlated with archwire stiffness, bracket slot length, archwire dimension and contact angle. The apparent stiffness was directly correlated with archwire stiffness, bracket slot length and archwire dimension, but inversely correlated with the contact angle.

<u>Miscellaneous Measurements</u>

Friction and Load inherent in the Apparatus

The amount of friction and load inherent in the test apparatus was evaluated by inserting archwires in the two Damon 2 guide brackets without the presence of a test bracket. The results revealed negligible friction as the wires moved through the guide brackets (Figure 26). An appreciable amount of load (~40 gm-cm) was caused by the rotating cam and bracket mounting plate.

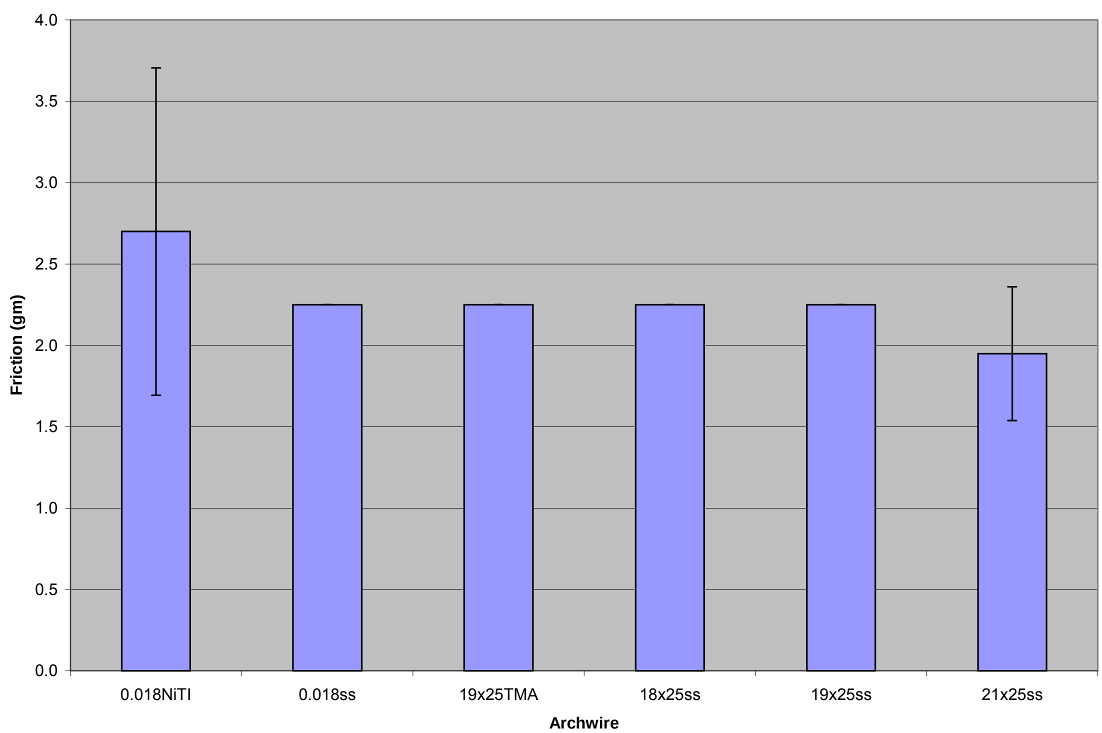

Figure 26. Graph showing that friction produced by the apparatus was negligible.

CHAPTER 5

DISCUSSION

Introduction

Many friction studies have been performed by attaching a bracket to a mechanical testing machine that measured friction, while an archwire was pulled through the bracket slot. This type of setup does not fully emulate the events that occur intraorally at the bracket-archwire interface. The aim of this study was to simulate, more closely, the effects of mastication on bracket-archwire interaction. More specifically, the friction between 6 different archwires and 4 different brackets were investigated while variable moments were placed at the bracket-archwire interface.

A 3-way ANOVA concluded that friction type, archwire, bracket and bracket-archwire interactions were all statistically significant at an alpha level of <0.0001.

Friction Types

Static friction and kinetic friction were similar, while dynamic friction was statistically significant. The dynamic friction was proportional to the dynamic load. Previous research stated that static friction was greater than kinetic friction. In this study, it did occur in 18 of the 24 bracket-archwire combinations. Static friction was 5 gm greater than kinetic friction, but this difference when evaluated by the Tukey-Kramer HSD analysis, at an alpha level of 0.05, was not statistically significant. Dynamic friction was statistically significant and greater than kinetic friction in 23 of the 24 bracket-archwire combinations. Dynamic friction was 62 gm greater than kinetic friction.

The static and kinetic friction were not statistically different, but these values were obtained with an archwire being pulled passively through the bracket slot. This finding may be different if a variable moment or an angle at the bracket-archwire interface was applied.

These results are clinically significant whenever sliding mechanics is involved. For tooth movement to occur, the static friction between the bracket and archwire must be overcome. This is most often accomplished with orthodontic devices such as rubber bands, powerchain and nickel-titanium coils pulling on the tooth. Once tooth movement has begun, its movement is maintained if kinetic friction is overcome. Tooth translation is a series of tipping movements involving crown tipping and then root uprighting. A tooth does not translate linearly along an archwire. When the bracket on the tooth crown is tipped in the direction it is being pulled, it will make contact with the archwire. It is at this point where binding may occur at the bracket-archwire interface; thus, impeding tooth movement. Therefore, a force must be placed at the bracket-archwire interface to release the binding, in order for tooth movement to continue.

This study simulated mastication and its effects at the bracket-archwire interface. Mastication, the impact of food on the archwire and bruxism can cause archwire deflection or cuspal flexure. It was hypothesized that these factors would release the binding that occurred at the bracket-archwire interface. The results revealed that a binding and releasing effect occurred when a dynamic load, such as a variable moment simulating mastication, was placed at the bracket-archwire interface; thus, enabling tooth movement.

Variable moments tipped (rotated) the bracket to a total range of 20^{o}, creating a variable bracket-archwire angle. During each trial, the archwire was subjected to cyclical binding and releasing actions against the bracket slot, due to bracket tipping. As binding occurred, the friction increased until the tip was reversed in the opposite direction; thus, releasing the binding and causing the friction to be reduced to less than that of kinetic friction. Intraorally, release of any binding present at the bracket-archwire interface would allow tooth movement. Such a reduction of dynamic friction seemed to be independent of the bracket and archwire.

Only elastomeric ties and self-ligating clips were investigated; however, it would appear that stainless steel ties would produce similar results. Therefore, the results of this study do concur with those of O'Reilly,[1] Braun[83] and Liew.[85] They stated that with archwire deflection, frictional resistance was either reduced or momentarily became zero, due to the release of binding.

Archwires

A generalized view of frictional resistance for each archwire was plotted in Figure 19 and the archwire groupings were indicated in Figure 20. The 0.018NiTi archwire was similar to 0.018ss and 18x25ss archwires. Its dimension was similar to and friction greater than 0.018ss, possibly due to the nickel-titanium content which produced greater friction than stainless steel, as stated in previous studies.[7,14,17,18,21,30,33,35,39,41,45,48,52,53,57,58,59,72,88] However, as stated earlier, the difference in friction between 0.018ss and 0.018NiTi were not always statistically significant. Although the 0.018NiTi archwire had a smaller dimension than the18x25ss archwire, the nickel-titanium content possibly increased the friction to approximate that of the18x25ss archwire, depending on the bracket. The three archwires 18x25ss, 19x25TMA and 19x25ss were not statistically different, despite their differing cross-sections and compositions.

The archwire with the highest friction was 21x25ss. For most test conditions, this archwire produced friction that was much greater than the other 5 archwires. These results indicated that when sliding mechanics were involved, smaller dimension archwires produced less friction than larger dimension archwires. The choice of which archwire to use for sliding mechanics also depends on the amount of tooth tip, torque and angulation required. The bracket prescription would be expressed more if a larger sized rectangular archwire was inserted into the bracket slot. Therefore, if one needs to maintain the proper tooth tip, torque and angulation, an 18x25ss, 19x25ss or 21x25ss archwire would be needed. If the amount of tooth translation is minimal, or tooth tip, torque and angulation were not of concern, a 0.018ss archwire could be used due to its low frictional resistance.

The average hardness values of the various archwires were provided by Ormco. Vickers hardness values for stainless steel, TMA and nickel-titanium archwires were 479, 296 and 273, respectively. This indicated that the TMA and nickel-titanium archwire were about 60% and 57% less hard than the stainless steel archwire, respectively. Therefore, binding of the 19x25TMA archwire against the bracket would occur to a greater degree when compared to 19x25ss, due to its reduction in hardness and greater "gouging" of the surface.

Brackets

A Tukey-Kramer HSD analysis concluded that the Minitwin and Transcend 6000 brackets were similar. The In-Ovation and Damon 2 brackets were both statistically different from one another and to the Minitwin and Transcend 6000 brackets. The slot of the Minitwin bracket was composed of stainless steel while the slot of the Transcend 6000 bracket was made of ceramic. The older generation Transcend 2000 ceramic bracket was found to have a rougher and more porous surface than stainless steel.[30,55] The friction in the newer Transcend 6000 bracket was not statistically significant from the Minitwin bracket in this study. This may be due to improved manufacturing processes that yielded a surface that was smoother and had a similar frictional resistance to stainless steel. When examined under a light microscope, the Transcend 2000 and Transcend 6000 brackets both appeared to have a similar surface roughness. The mesial and distal edges of both bracket slots were square; however, only the facial surface of the Transcend 6000 bracket was rounded. Therefore, the belief that all ceramic brackets produce greater friction than stainless steel brackets was not supported.

The In-Ovation and Damon 2 brackets were, in general, statistically different. The In-Ovation bracket had an active self-ligating clip while the Damon 2 bracket had a passive self-ligating clip. Both produced less friction than the Minitwin and Transcend 6000 brackets. The In-Ovation bracket "grabbed" at an archwire dimension of 0.018 x 0.025-inches when pulled with finger pressure, due to the active self-ligating clip. No resistance was encountered with the Damon 2 bracket up to and including an archwire dimension of 0.021 x 0.025-inches. This indicated that the active self-ligating clip of the In-Ovation bracket would bind more to an archwire than the passive self-ligating clip of the Damon 2 bracket. Therefore, higher friction would be encountered with the In-Ovation bracket when 0.018 x 0.025-inch and greater archwire dimensions were inserted into its bracket slot, when compared to the Damon 2 bracket. The active engagement of the archwire into the bracket slot allows the tip, torque and in-out features of the In-Ovation bracket to be more fully expressed than in the Damon 2 bracket.

Bracket-Archwire Interactions

When the static and kinetic frictions were averaged for each bracket-archwire combination, the Minitwin and Transcend 6000 brackets produced higher levels of friction than In-Ovation and Damon 2 brackets (Figure 23). This came as no surprise due to previous research which concluded that conventional brackets tied with elastomerics or steel ties produced greater friction than self-ligating brackets.[23,65,88] When elastomers and stainless steel ties were ligated to a bracket, the archwire was pushed into the bracket slot. This increased the normal force acting on the archwire, which caused an increase in friction. The debate on whether elastomers or steel ties produce greater friction has not been concluded.

The two self-ligating brackets produced a similar amount of friction for both the 0.018NiTi and 0.018ss archwires because they passively slid through the closed bracket slots. With the remaining rectangular archwires, the In-Ovation bracket produced greater friction than the Damon 2 bracket, due to its active self-ligating clip which engaged the archwire.

The In-Ovation and Minitwin brackets produced the same amount of friction with the 18x25ss archwire. This could be due to the active self-ligting clip of the In-Ovation bracket behaving like the elastomeric tie on the Minitwin bracket for the 18x25ss archwire. Both may have exerted an equivalent amount of normal force on the archwire; thus, producing a similar amount of friction.

The increased friction by the In-Ovation and Damon 2 brackets, over the Minitwin and Transcend 6000 brackets, with the 19x25TMA may be due to the composition of the archwire and the nature of ligation. The TMA material was less hard and more flexible. The decreased hardness may play a significant role when comparing the conventional brackets to the self-ligating brackets. With the conventional Minitwin and Transcend 6000 brackets, the 19x25TMA archwire was pushed into the bracket slot with an elastomeric tie, which was also soft and flexible. Since both the 19x25TMA and elastomeric tie were both soft and flexible, any binding that may have occurred would primarily happen at the bracket-archwire interface. Less binding would occur between the archwire and the elastomeric tie.

However, with the self-ligating In-Ovation and Damon 2 brackets, they had a stainless steel gate instead of an elastomeric tie. The stainless steel gates were hard, inflexible and may have rough edges, compared to elastomeric ties. The In-Ovation bracket produced greater friction than the Damon 2 bracket with the 19x25TMA. The In-Ovation bracket had an active self-ligating clip, which was pushed up against the 19x25TMA archwire, which was soft and flexible. This may have caused the active clip to dig into the 19x25TMA archwire; thus, creating binding and increasing friction. Since the Damon 2 bracket had a passive self-ligating clip, it did not push up against the 19x25TMA archwire. Its metal gate formed the fourth wall to enclose the archwire, yet still allowed it to freely move within the bracet slot. This fourth wall of the Damon 2 bracket, although being passive, was not soft and flexible like an elastomeric tie. Therefore, the metal gate could still bind to the softer 19x25TMA archwire causing increased friction.

The 19x25TMA archwire produced greater friction than the 18x25ss and 19x25ss archwire in combination with the In-Ovation and Damon 2 brackets. This may be due to the reasons given above. The 19x25TMA archwire material was less hard than that of stainless steel. Therefore, the metal gates of both self-ligating brackets would bind more to the TMA than stainless steel archwire.

In general, the conventional brackets and self-ligating brackets formed two distinct groups for the 0.018NiTi and 0.018ss in Figure 23 and Figure 24. The Minitwin and Transcend 6000 brackets yielded greater friction than the In-Ovation and Damon 2 brackets. This is due to the small archwire dimension, which passively inserts through the In-Ovation and Damon 2 bracket slots, but is actively held against the bracket slot for the Minitwin and Transcend 6000 brackets by an elastomeric tie. Therefore, friction was greater with the conventional brackets.

Dynamic Load vs Dynamic Friction

As the slope of the dynamic load increased, the slope of the dynamic friction also increased, and vice-versa. Therefore, it appeared that both dynamic load and dynamic friction were synchronized. O'Reilly[1] found the relationship between displacement and friction to be linear. Braun[83] stated that reduction of frictional resistance was proportional to the magnitude of the oscillations.

Archwire Dimension

The archwire dimension was measured in order to calculate the contact angle. All archwires were measured to the manufacturer specifications, except the 19x25TMA and 19x25ss archwire which were 0.001-inch smaller on the larger dimension of the archwire. In this study, the variable moments placed at the bracket-archwire interface were rotated about side 2, which is the larger dimension of a rectangular archwire. Therefore, the side 2 wire stiffness numbers were used for comparison.

Bracket Slot Length

The bracket slot length was measured in order to calculate the contact angle. Although the Minitwin and Transcend 6000 brackets were not statistically different for friction, the difference in bracket slot length was 0.70 mm. The In-Ovation bracket was 0.37 mm greater in bracket slot length then the Minitwin bracket; however, in general, the In-Ovation bracket produced less friction. This would indicate that bracket slot length alone did not influence frictional resistance. However, the bracket slot length would affect the interbracket distance. A wide bracket slot would lead to a decreased interbracket distance, and this would aid in rotation corrections. A narrow bracket slot would lead to an increased interbracket distance, and this would aid in archwire engagement into the bracket slot.

Contact Angle

The contact angle was measured using Kusy's formula.[133] As the contact angle increased, from 0.5^o to 2.3^o, there was a general trend for decreased mean apparent stiffness. The smallest contact angle was between the Transcend 6000 and In-Ovation brackets with the 21x25ss archwire. The largest contact angle was between the Damon 2 bracket and the 0.018NiTi, 0.018ss and 18x25ss archwires. These results are due to the size of the archwire and bracket slot.

If the bracket was tipped less than the contact angle, binding would not occur. However, if the bracket was tipped more than the contact angle, binding would occur and consequently, friction would increase.

Apparent Stiffness

There was no difference between the dynamic load and apparent stiffness. This indicated that when variable moments were placed at the bracket-archwire interface, with or without the archwire being pulled, the load stayed constant. Hence, archwire pull did not influence the dynamic load or apparent stiffness.

There was a direct correlation between archwire stiffness, bracket slot length and archwire dimension and an inverse correlation with contact angle to apparent stiffness. The archwire stiffness, archwire dimension and contact angle were inter-related to a great degree.

The variable moment created a maximum bracket-archwire angle of 20^o for all trials. Therefore, the load necessary to achieve this constant angle would vary with archwire stiffness. More flexible materials such as nickel-titanium and TMA require less force to create the bracket-archwire angle of 20^{o}, when compared to stainless steel archwires. The 19x25TMA archwire produced a mean apparent stiffness that was half that of the 19x25ss archwire.

The size and shape of the archwire contributed to the apparent stiffness as well. When comparing 0.018ss (66 gm-cm) to 18x25ss (131 gm-cm), the rectangular archwire had more apparent stiffness than the round wire. The 18x25ss (131 gm-cm) had less apparent stiffness than the 19x25ss (244 gm-cm), even though the difference in archwire dimension was just 0.001-inch on only one side. Therefore, as the archwire dimension increased, both the archwire stiffness increased and the contact angle decreased; thus, producing a greater apparent stiffness.

<u>Miscellaneous Measurements</u>

Friction and Load inherent in the Apparatus

The amount of friction inherent within the friction testing apparatus was negligible (2.1 gm); therefore, the friction obtained from every trial was friction at the bracket-archwire interface.

However, the amount of load inherent within the tipping apparatus was appreciable (40 gm-cm). Since this value was consistent for all trials (and could have been subtracted from every trial) the results were valid.

One of the goals of this study was to evaluate for friction trends between 6 archwires and 4 brackets, not raw data values. Previous studies that measured friction involving archwire deflection were performed with different set-ups and therefore, obtained different raw data. Hence, the results of this study may not coincide with other investigations. The results from this study would aid orthodontists in their selection of which bracket-archwire combination would be the most efficient when performing sliding mechanics.

Clinical Implications

As with all *in vitro* studies, the results may vary with what actually occurs *in vivo*. However, since it is nearly impossible to replicate variable moments intraorally at the bracket-archwire interface, the results obtained from this study are the most realistic yet. Most of the previous studies have pulled an archwire through a bracket slot in a linear fashion; thus, not simulating the variable moments that occur intraorally during mastication. The results from this study indicate that during mastication, a binding and releasing effect occur at the bracket-archwire interface. In other words, when sliding mechanics is involved, binding between the bracket and archwire may occur, which will impede further tooth movement, until the binding is released.

It is known that tooth translation is a series of tipping movements. For example, if canine retraction is desired, its crown is tipped distally until the bracket contacts the archwire. Then the root is uprighted by being tipped distally. Thus, tooth translation is a series of crown tipping and root uprighting. When the bracket on the crown of the tooth tips to contact the archwire, it is at this interface where binding can occur. The root cannot upright itself until the binding is released; hence, tooth translation is stopped. Therefore, during mastication, when food impacts the archwire causing it to deflect or cuspal flexure occurs, it may release the binding that may be present at the bracket-archwire interface; thus, allowing tooth movement to continue.

This phenomenon was seen in the study. When the bracket was tipped, the archwire contacted the edges of the bracket slot causing friction to increase. However, when the bracket was tipped in the opposite direction, similar to archwire deflection during mastication, the friction decreased due to the release of binding. As a result, sliding mechanics occurred.

These results indicate that tooth translation involves many factors such as archwire dimension and composition, bracket composition, method of ligation, binding, archwire deflection and cuspal flexure. Although this study was performed *in vitro*, many of the results can be applied *in vivo*. The choice of which bracket and archwire to use for sliding mechanics influences the efficiency of tooth movement. This study revealed that self-ligating brackets produced less friction than conventional brackets. Therefore, if friction is to be minimized, the In-Ovation and Damon 2 self-ligating brackets should be used in place of the Minitwin and Transcend 6000 brackets. The round archwires produced less friction than the rectangular archwires. During tooth translation, stainless steel archwires are most often used, due to their stiffness. Therefore, the round 0.018-inch stainless steel archwire should be used to minimize friction. However, if a rectangular stainless steel archwire is used during sliding mechanics, the smallest dimension archwire would yield the least amount of friction.

Future Studies

A repeat of this study with other brackets and archwires would be beneficial. Although the Transcend 6000 bracket was tested in this study, its use has declined due to the popularity of the new Clarity brackets, also produced by Unitek. This and other esthetic brackets, with and without a stainless steel slot, composed of different materials such as plastic and ceramic, could be investigated to evaluate their influence on friction.

With self-ligating brackets, there is no need for elastomeric ties; however, some children want colors to be placed on the brackets, and this is routinely done. A study to investigate frictional differences in self-ligating brackets with and without an elastomeric tie could be performed. A self-ligating esthetic bracket could be tested to determine if the friction is more similar to ceramic brackets or self-ligating brackets.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The purpose of this study was to determine whether self-ligating brackets exhibited less friction than stainless steel and ceramic brackets when subjected to variable moments. Few studies have investigated the influence of mastication, archwire deflection and cuspal flexure on friction at the bracket-archwire interface.

Statistical analysis was performed using ANOVA ($p<0.0001$) and Tukey-Kramer HSD ($p<0.05$). Friction types, archwires, brackets, bracket-archwire interactions and apparent stiffness were evaluated. Bracket slot length, archwire dimension and contact angle were measured.

The following general conclusions were made:

1) Static and kinetic friction were similar, while dynamic friction was statistically different.
2) The following groups of archwires produced similar friction: 1) 0.018ss and 0.018NiTi 2) 18x25ss, 19x25TMA and 19x25ss 3) 21x25ss
3) The Minitwin and Tanscend 6000 brackets produced a similar amount of friction, while the In-Ovation and Damon 2 brackets were statistically different from one another and to the Minitwin and Transcend 6000 brackets.

The following specific conclusions were made:

1) Bracket-archwire interactions

   a. The conventional Minitwin and Transcend 6000 brackets produced greater friction than the self-ligating In-Ovation and Damon 2 brackets, except with the 19x25TMA archwire.

   b. In-Ovation and Damon 2 brackets produced similar amounts of friction with 0.018NiTi and 0.018ss archwires.

   c. Dynamic friction was momentarily reduced below kinetic friction. It was at this point where binding at the bracket-archwire interface was released.

2) Dynamic load was proportional to dynamic friction.

3) Contact angle and bracket slot length did not greatly influence frictional resistance, for the conditions of this study.

CHAPTER 7

RECOMMENDATIONS FOR FUTURE RESEARCH

Upon completion of this study, the following were recommended:

1) Using brackets with 0^{o} torque and 0^{o} tip would facilitate and ensure that the brackets, when mounted onto the acrylic rods, were properly aligned.
2) The 0.018NiTi used in this study was cut from a preformed archwire; thus, leaving one end curved. If a straight piece of nickel-titanium wire, with the same length as the other archwires being investigated, can be found, this would eliminate one variable from the current study.
3) The Instron machines' vice-like grips, that hold the archwire, were serrated. Having a smooth surface grip would prevent any bending of the archwire that may occur. This would ensure total passivity of the archwire through the bracket slots.
4) The friction-test apparatus was designed and built to be user friendly. When the test brackets and archwires were passively aligned, many small adjustments were still necessary. This increased the time required to perform the study. Redesigning the test-apparatus to minimize the numerous small adjustments necessary to ensure bracket-archwire passivity would improve efficiency

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