FRICTION IN SLIDING ORTHODONTIC MECHANICS: CERAMIC BRACKETS, TEFLON-COATED WIRES, AND COMPARATIVE RESISTANCES

James R. Gill, D.D.S.

A Thesis Presented to the Faculty of the Graduate School of Saint Louis University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Dentistry

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FRICTION IN SLIDING ORTHODONTIC MECHANICS: CERAMIC BRACKETS, TEFLON-COATED WIRES, AND COMPARATIVE RESISTANCES

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A Digest Presented to the Faculty of the Graduate
School of Saint Louis University in Partial
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DIGEST

In response to patient "demand" for more esthetic orthodontic appliances, brackets of aluminum-oxide ceramics and Teflon-coated archwires and ligature wires are now available to the practitioner. The round, coated archwires 0.018 inches in diameter are potentially useful during cuspid retraction procedures in bicuspid-extraction orthodontic treatment. Controlled evaluation of frictional forces associated with the ceramic brackets and coated archwires (compared to conventional appliance components of stainless steel) has apparently not been reported in the literature to date.

The objective of the present investigation was to measure and compare the magnitudes of frictional forces generated within a relevant sample of brackets, archwires, and ligations during simulated orthodontic edgewise sliding mechanics. Independent variables and their values were 1) bracket (stainless steel, single-crystal ceramic, and polycrystalline ceramic), 2) archwire (uncoated and Teflon-coated stainless steel), and 3) ligation (uncoated and Teflon-coated stainless-steel wires). A total of 144 bracket/archwire/ligation specimens were tested, each immersed in a saliva-substitute medium to simulate intra-oral conditions: six replications of each combination of independent variables in a 3 X 2 X 2 format within primary subsamples defined by zero and five degrees of relative bracket-slot/archwire angulation.

Plots of frictional force versus relative displacement were generated by a recorder attached to a universal testing machine. Dependent variables quantified were maximum static and mean kinetic frictional forces (the latter being the average frictional force generated during a 1.1 millimeter movement of the bracket along the archwire segment). With the sample halved by angulation, analyses of variance were performed, and Tukey's Honestly Significant Difference post-hoc test was used.

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The statistical outcomes indicated that, with coated or uncoated archwires, polycrystalline brackets generated larger frictional forces than either stainless-steel or single-crystal brackets. Teflon-coated archwires in slots of either ceramic bracket generated smaller frictional forces than uncoated archwires, although the ceramic brackets tended to cause greater distressing of the surfaces of both archwires than did the stainless-steel brackets.

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L. William Nesslein

Clinical Professor George S. Uchiyama

DEDICATION

With great love and affection, this work is dedicated to Terri, whose encouragement, counsel, endurance, and love made the completion of this task possible.

ACKNOWLEDGEMENTS

The author wishes to acknowledge Professor Robert J. Nikolai for his patient assistance and guidance during the preparation of this thesis and the United States Air Force for its financial support.

Sincere thanks is expressed to the faculty and staff of St. Louis University for sharing their knowledge and expertise over the past two years; and to Dr. Lysle E. Johnston, Jr. for teaching "his" students, by word *and* deed, that the specialty of orthodontics depends on the diligent pursuit of academic and technical excellence.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

A "demand" by orthodontic patients for more esthetic appliances has resulted in the recent manufacture, marketing, and use by the practitioner of orthodontic brackets and wires made of materials less visible against facial tooth crown surfaces than conventional appliance components of stainless steel. In particular, brackets of polycrystalline and single-crystal aluminum-oxide ceramics and Teflon-coated archwires and ligature wires are now available.

Knowledge and consideration of the frictional forces generated within an orthodontic appliance are necessary to determine the proper active-force magnitudes required to achieve a clinically desirable time-rate of tooth movement during sliding mechanics. The magnitudes of these frictional forces are dependent on several parameters that may be controlled clinically to a certain extent. The orthodontic literature contains considerable documentation on the effects of specific variables on friction, including archwire shape and size, occlusogingival and mesiodistal bracket-slot dimensions, relative angulation of the bracket-slot and archwire, interbracket distance, and ligation.

Experiments have also been undertaken to study frictional resistances to relative sliding displacements between contacting flat surfaces of various materials (including stainless steel and Teflon). Measurements of frictional forces between brackets of polycrystalline or single-crystal ceramics and archwires of Teflon-coated stainless steel, and comparison of these forces with forces associated with conventional stainless steel appliances have apparently not been previously reported in the literature.

Coated round archwires are presently available, and are potentially useful during cuspid-retraction procedures in bicuspid-extraction treatment. This investigation was undertaken, then, to measure and compare the magnitudes of maximum static and kinetic frictional forces generated within a relevant sample of bracket/archwire/ligation specimens during simulated orthodontic edgewise sliding mechanics. Specifically sought were the relative influences (comparisons to stainless-steel appliances) on orthodontic friction from polycrystalline and single-crystal ceramic brackets and Teflon-coated archwires and ligature wires.

CHAPTER TWO

REVIEW OF LITERATURE

The increase in recent years in numbers of adults seeking orthodontic treatment has been accompanied by a "demand" for improved esthetics in the orthodontic appliance (Flores, 1988). Application of materials engineering to orthodontics has resulted in the emergence of ceramic brackets as a viable option to conventional stainless-steel crown attachments. Composite archwires of stainless steel coated with polytetrafluoroethylene (PTFE; Teflon) have been marketed for use with these ceramic brackets. The effects of brackets and wire surfaces of these "new" materials on friction during orthodontic sliding mechanics has not been reported in the literature.

An overview of friction in sliding orthodontic mechanics will enhance the reader's understanding of the current research. The following topics are reviewed:

1) theory and principles of sliding friction;
2) friction in orthodontics;
3) controlled experimentation in bracket-wire friction; and
4) new orthodontic materials.

The chapter concludes by relating the present research with previous experimentation and existing knowledge, and projects how information gained may benefit the clinical orthodontist.

Theory and Principles of Sliding Friction

Sliding friction is the resistance to the relative displacement of contacting bodies in a direction tangent to the plane of contact; the resistance is due principally to the surface roughnesses and pushing contact forces between the bodies (Nikolai, 1985). According to Palmer (1951), the earliest known friction experiments were conducted by Leonardo da Vinci in the 16th century; however, reports of da Vinci's work were not reproduced and published until other investigators had conducted and documented similar findings independently. The French physicists Amontons, Coulomb, and Morin have been generally credited with defining the classical laws of friction in the 18th and 19th centuries. Palmer (1951) summarized these "laws" of sliding friction in four brief statements: 1) frictional force is directly proportional to the load (force between and perpendicular to the contacting surfaces); 2) frictional force depends on the nature of the sliding surfaces; 3) friction is independent of the area of contact between the surfaces; and 4) friction is independent of the sliding velocity.

Rabinowicz (1965) argued that frictional force is independent of the *apparent* area of contact; however, is dependent upon the *actual* area of contact. He explained this statement by describing events that occur at a molecular level when two surfaces slide over one another. According to the adhesion theory of friction, the relative (tangential) displacement of the contacting areas of two surfaces accounts for most of the energy expended when the two surfaces move over one another; that is, mechanical work is required to break the bonds that form between surface molecules at points of actual contact. Although virtually impossible to separate in occurrence, the increased area of actual contact that occurs when greater contact pressure is induced, and not the force itself, is the direct cause of greater friction. This phenomenon is illustrated by considering that, although very rough contacting surfaces may exhibit substantial friction because of the need to lift the asperities of one surface over another, very smooth surfaces may generate even greater friction under the same pushing force between them. This greater friction is due to the increased area of actual contact.

Rabinowicz (1965) also described exceptions to these "laws" of friction. If a hard surface is in contact with a much softer one, during relative displacement of the two surfaces the edge or irregularities of the hard surface may dig into the softer material. This phenomenon is termed the "plowing component" and, when observed, the first "law" described does not apply. Deviations from the third and fourth "laws" may occur under conditions not ordinarily encountered in orthodontic situations; that is, with very smooth or clean surfaces, or with very high velocities.

Friction in Orthodontics

The initiation of tooth movement by orthodontic forces may be either desirable or undesirable. Anchorage, used in an orthodontic context, is defined as "resistance to unwanted tooth movement" (Proffit, 1986). In wholly intra-oral canine-retraction procedures, for example, increased friction in the canine bracket-slot/archwire/ligation system necessitates the use of greater applied force to cause the desired tooth movement. The accompanying larger responsive force acting on the posterior "anchorage" teeth can, in turn, cause undesirable movement of these teeth in an anterior direction (i.e., produce "loss" of anchorage). The awareness and management of frictional forces is, therefore, an important consideration when planning orthodontic tooth movement (Proffit, 1986).

Friction is created when two contacting surfaces slide or attempt to slide with respect to one another. Frictional force is at least part of the responsive counterpart to some initial force causing or attempting to cause motion, and the magnitude of the frictional resistance is influenced by the nature of the contacting surfaces and the "normal" forces (action-reaction components perpendicular to the contact plane) exerted on the contacting areas (Nikolai, 1985). As noted earlier, increased normal force results in an increased actual area of contact that is the ultimate cause of increased friction at a molecular level (Rabinowicz, 1965). In the following discussion, however, the classical (Coulomb) frictional model that correlates increased normal force *directly* to increased friction is assumed to facilitate a clearer discussion of clinical forces.

Bracket-Wire Contacts

During sliding orthodontic mechanics in an edgewise system, the contact relationships between archwire, bracket-slot, and ligation affect the level of frictional force (Nikolai, 1985). These contacts exist in all planes of a three-dimensional orthodontic appliance system, and cause forces that combine to create the total frictional resistance. To facilitate an understanding of the principles involved, the following discussion considers contact relationships and forces as viewed from the facial and occlusal perspectives.

Assuming the bracket-slot size is greater than the occlusogingival dimension of the archwire, contact viewed from the facial perspective (Fig. 2-1) may occur in one of three formats: 1) archwire and bracket slot are parallel (zero degrees angulation), and the archwire contacts the bracket-slot along the length of

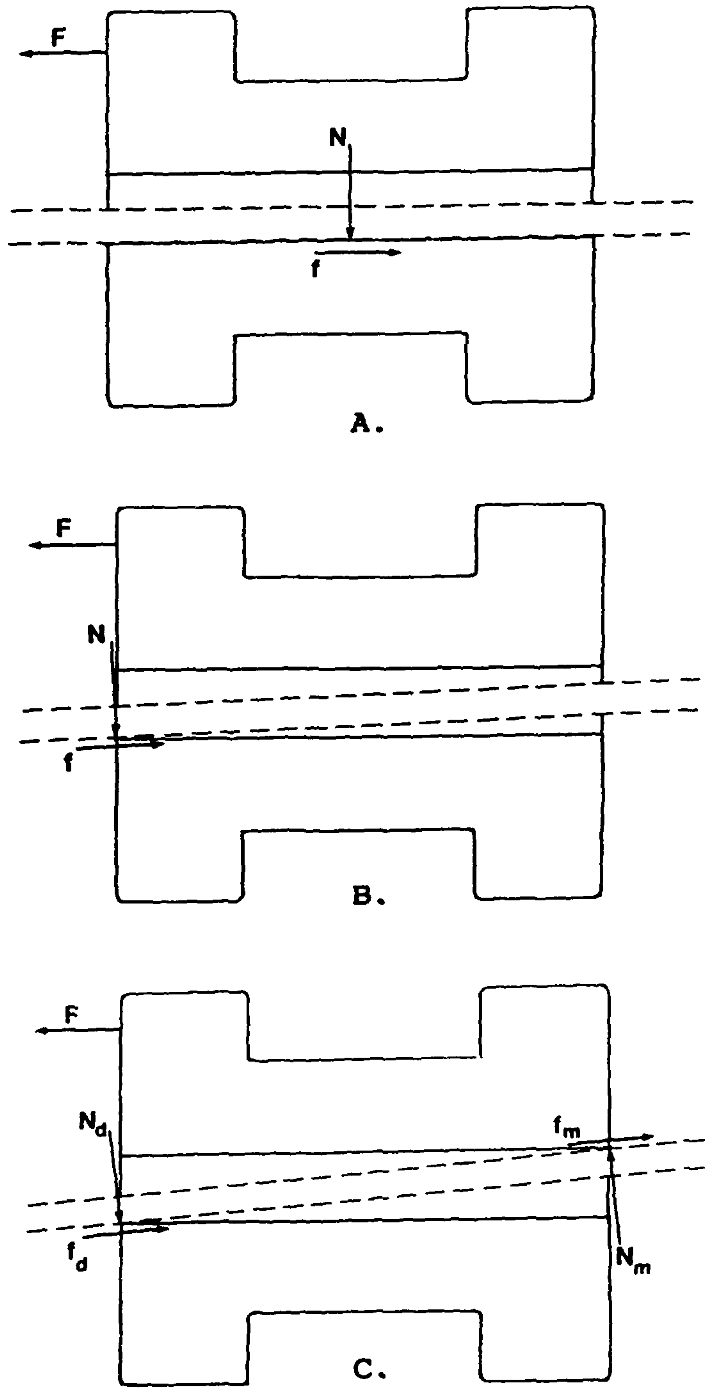


Fig. 2-1. Bracket-slot/archwire contacts. Facial view of a maxillary right canine bracket with (A) bracket-slot and archwire parallel; (B) slight angulation; (C) second-order clearance eliminated.

either its occlusal or gingival wall, creating a normal force (N) and resistance to movement (f) along that contact area (Fig. 2-1A); 2) the archwire is tipped occlusogingivally with respect to the bracket-slot sufficiently to allow contact of the archwire at only one bracket-slot edge, creating a normal force (N) at that point (Fig. 2-1B); or 3) archwire and bracket are tipped occlusogingivally with respect to one another such that second-order clearance is eliminated. When this third format exists, the bracket-slot/archwire contacts generate normal forces at diagonally-opposite mesial (N_m) and distal (N_d) slot edges, with corresponding frictional resistance at these points (f_m , f_d) (Fig. 2-1C). All three contact formats may typically occur during various stages of tooth movement.

The magnitudes of the normal forces generated at the two diagonally-opposite slot edges after second-order clearance has been eliminated are directly related to the angulation between the archwire and bracket-slot in their passive configurations. Increased normal forces at contact points (round wire) or along contact lines (rectangular wire) on the bracket-slot edges (created by increased angulation) cause greater frictional resistance to movement (Frank and Nikolai, 1980).

From an occlusal perspective, contact between an archwire and bracket-slot can generate the normal force (N_{bkt}) and frictional force (f) distributed over the slot surface (as shown, Fig. 2-2), or at only the mesial or distal aspect, if contact is limited to one edge. In addition, the ligation (steel wire, elastomer, brass pin, etc.) will cause normal force(s) (N_{lig}) and corresponding frictional resistance (f_{lig}) along the facial aspect of the archwire at each point of contact. Each of these frictional components contributes to the total frictional resistance in a bracket/archwire system (Frank and Nikolai, 1980).

Static versus Kinetic Friction

Two related forms of sliding friction are important in orthodontic mechanics: static (before motion) and dynamic (or kinetic, during motion) (Nikolai, 1985). *These forces are illustrated by the classical* friction model exhibited by a block on a horizontal, flat plane, for example (Fig. 2-3). At rest, the weight of the block (Wt) is balanced by an equal and opposite force (N) that is exerted by the supporting surface and is perpendicular to the plane of contact. This component is the normal force. When force (F), is applied tangential to the contact plane in a manner that attempts to dislodge the block, but with a magnitude insufficient to cause motion, the resistance to motion is termed *static* (motionless) friction (f_s). In normal forces (N_{bkt}) along the entire lingual aspect of this static situation, the algebraic sum of the horizontal forces acting to cause and resist motion is equal to zero (Beer and Johnston, 1984).

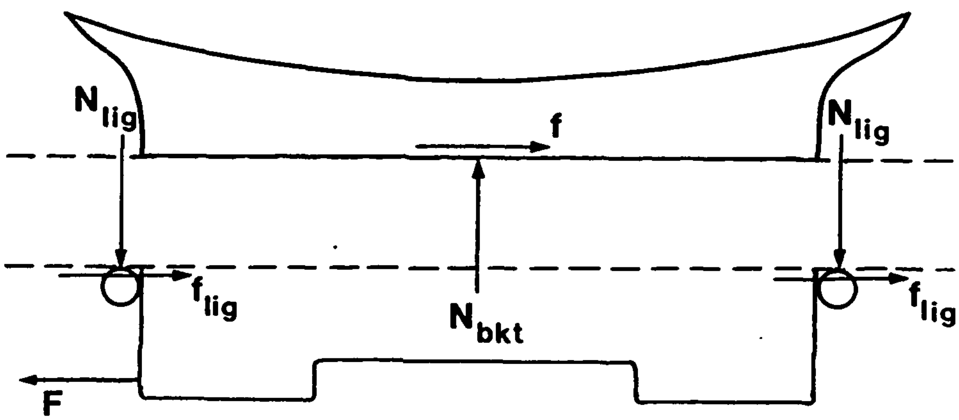
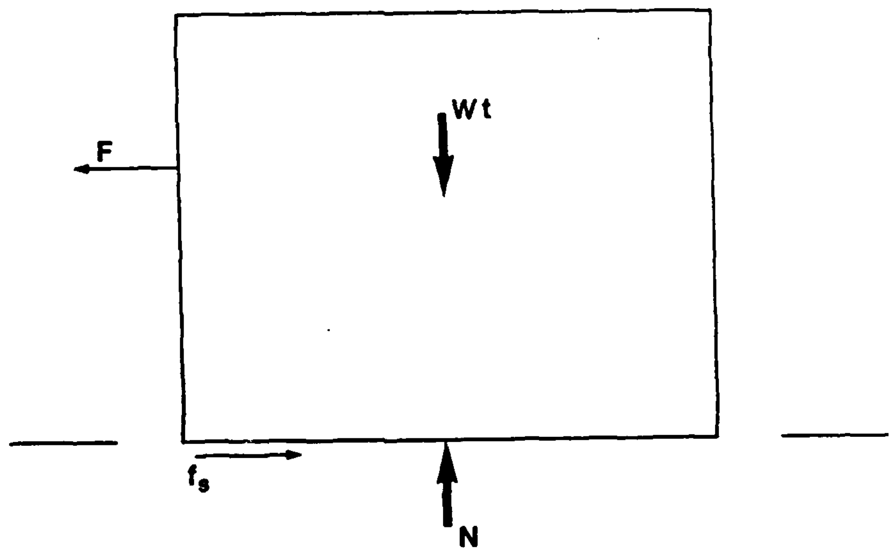
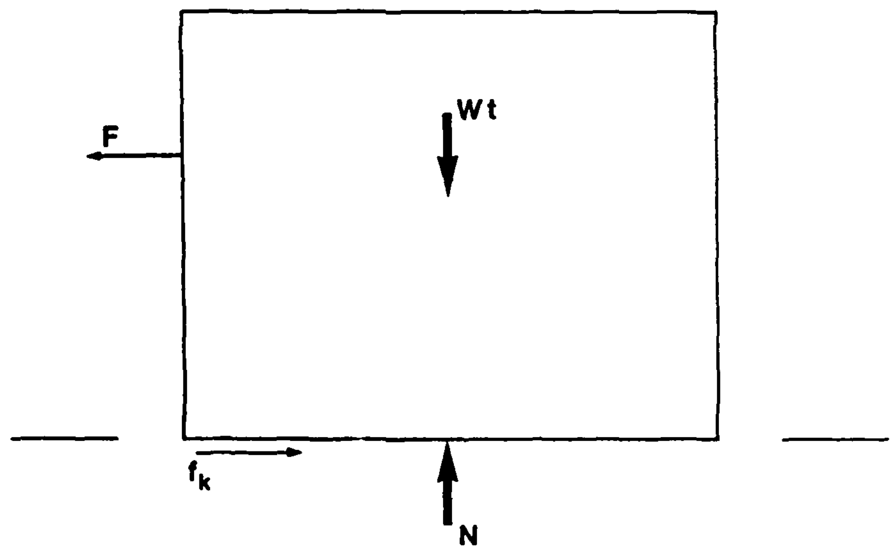


Fig. 2-2. Bracket-slot/archwire/ligature-wire contacts. Occlusal view of a maxillary right canine bracket.



A) No Motion ($F = f_s$)



B) During Motion ($F > f_k$)

Fig. 2-3. Simple frictional force model displaying forces between a block and a flat plane prior to motion (A) and during motion (B).

It is evident from the above description that an increased magnitude of force acting to cause motion causes a concurrent increase in the static frictional force resisting that motion. This relationship exists until the force resisting motion reaches its maximum value. Any motive force greater than this maximum value will cause movement ($F > f_s$). The magnitude of frictional resistance that must be overcome in order to initiate motion has been appropriately termed the "maximum static frictional force" (Frank and Nikolai, 1980). Immediately upon the initiation of movement, however, the frictional force opposing movement generally decreases slightly ($f_k < f_s$) (Beer and Johnston, 1984).

<u>Friction During Orthodontic Tooth Movement</u>

Tooth movement occurring as a result of the application of orthodontic forces is governed by a combination of biological and mechanical factors (Fig. 2-4). Initially, the force of appliance activation (F) should be greater than the combined resistances of the periodontal ligament (PDL) and static friction ($F > f_{pdl} + f_s$). This inequity causes tooth movement via deformation of supporting periodontal structures and, concurrently, a relative displacement of the bracket and archwire. Fig. 2-4A depicts these orthodontic forces during initial tooth movement, prior to elimination of second-order clearance (a simple-tipping movement). Motion continues until the combined resist

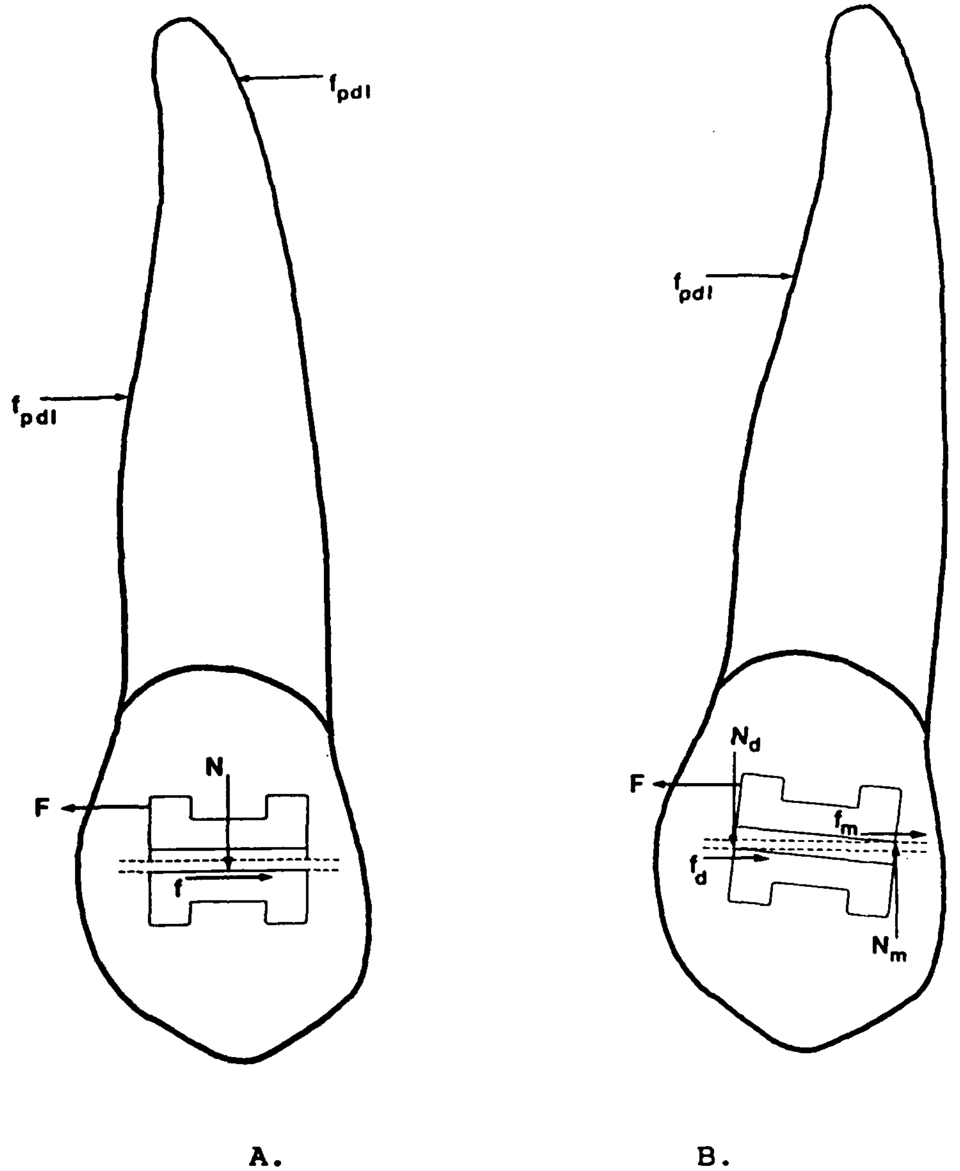


Fig. 2-4. Frictional forces during tooth movement. Simple tipping movement with bracket-slot and arch-wire initially parallel (A); translatory tooth movement following elimination of second-order clearance (B).

ances of the ligament and kinetic friction are equal to the delivered force ($f_{pdl} + f_k = F$). This "static" situation occurs as a combined result of deactivation of the motive force (e.g., from an elastomeric module) and increased resistance of the deformed periodontal structures. The system is now at "equilibrium", and motion ceases.

During this "motionless" period of time, several inter-related events that may ultimately allow the resumption of tooth movement are occurring simultaneously. Osseous remodeling occurs adjacent to the compressed periodontal ligament, and decreases the biologic resistance to tooth movement. Concurrently, the level of maximum static frictional force that must be overcome to allow resumption of tooth movement is affected by the normal forces generated among bracket-slot/archwire/ligation contacts. During a simple-tipping tooth movement, normal forces against the bracket-slot are exerted primarily against the facial surface by the archwire, and are a function of the force of ligation. During a translatory (or bodily) tooth movement, additional forces are exerted against diagonally-opposite mesial and distal bracket-slot edges by the archwire. These normal forces may be altered by mastication, occlusal forces, and wire resilience.

The "motionless" state exists until the combined resistances of the periodontal ligament and static friction are smaller than the applied force ($f_s + f_{pdl} < F$). Movement is thereby re-initiated, and continues until, once again, the combined resistances of the ligament and kinetic friction are equal to the delivered force. This sequence occurs over and over during the course of tooth movement, resulting in a series of "jumps" or "steps" rather than smooth, continuous movement. Commensurate with each of these steps, appliance "deactivation" (i.e., shortening of an elastomeric module) causes a decreased magnitude of the motive force delivered to the tooth. With time, this deactivation may result in a motive force that is inadequate to overcome resistances, and the displacement process ceases (Frank and Nikolai, 1980).

Surface Roughness

The relationship between surface roughnesses of orthodontic appliance components and friction is not as well defined as the relationship between planar surfaces and friction. "Surface roughness" may refer to the *absolute* roughness of a single surface (e.g., of a bracket-slot or archwire), or the *relative* roughnesses of two contacting surfaces. Controlled experimentation involving plane surfaces has shown that "maximum friction and the level of frictional force following the initiation of motion are highly dependent on the relative roughnesses of the contacting surfaces..." (Nikolai, 1985). Though not proven, a similar correlation between archwire and bracket-slot surface roughnesses and friction during orthodontic sliding mechanics is suspected (Kusy, Whitley, Mayhew, and Buckthal, 1988). Although distinct differences among the absolute surface roughnesses of various archwire materials have been demonstrated (Kusy et al., 1988), the impact of these differences (or similar differences among bracket surfaces) on friction in sliding orthodontic mechanics has not yet been demonstrated.

Experimentation in Bracket/Wire Friction

Clinical Observations

Early mention of friction in the orthodontic literature was by Stoner (1960) who made the clinical observation that "recognition must always be given the fact that, because of appliance inefficiency, sometimes applied force is dissipated by friction or improper application, and it is difficult both to control and to determine the amount of force that is being received by the individual tooth." Other authors have suggested how the design of a particular orthodontic appliance impacted friction clinically (Begg, 1962; Sims, 1964; Gottlieb, Wildman, Hice, Lang, Lee, and Strauch, 1972; Schudy, 1975; Kesling, 1988). These reports, however, were anecdotal in nature and apparently based on clinical observation without the support of documented research.

Effects of Bracket-Wire Angulation, Size, and Materials

Nicolls (1968) used a dynamometer to measure frictional forces generated between welded "ripple" brackets, welded tubes, or soldered tubes, and various light round wires. Two experimental models were used: a typodont to simulate intraoral conditions; and a device to measure friction while bracket-slot widths and angulations were controlled. He concluded that frictional force varied directly with increased angulation or slot width, and that binding occurred more "suddenly and severely" with narrow than with wide brackets.

Andreasen and Quevedo (1970) developed a more sophisticated testing apparatus than that described by Nicolls to study the force of friction generated between archwire and bracket-slot in a simulated canine-retraction movement. The device allowed them to hold constant the anteroposterior distances between brackets representing teeth adjacent to the simulated cuspid, and to maintain a (reportedly) consistent force on the cuspid ligature via a compressed coil. Repeated measures were analyzed to determine the maximum frictional force between bracket-slots and wires with varying angulations, sizes of archwires, and test conditions (wet versus dry environment). They found that friction varied directly with increased angulation or wire size, and that neither bracket width nor saliva lubrication had a significant influence.

In separate experiments, Frank and Nikolai (1980) and Petersen, Spencer, and Andreasen (1982) investigated similar influences on bracket-slot/wire friction.

Results of both studies supported Andreasen and Quevedo's contention that increased wire size or increased angulation created greater friction; however, Frank and Nikolai reported that friction also varied *directly* with bracket-slot width. This claim is contrary to the contention of Kamiyama and Sasaki (1973) and Thurow (1982) that slot width and friction are *inversely* related. Evaluation of experimental designs, however, seemed to resolve the apparent conflict.

Frank and Nikolai (1980) tested brackets of various mesiodistal slot widths at *fixed* angulations to determine the maximum static frictional force developed between bracket-slot and archwire. The apparatus used by Kamayami and Sasaki (1973), however, measured the forces required to overcome bracket-archwire friction in systems with simulated biologic resistance and varying mesiodistal slot widths; angulation was not a controlled variable. Although not specifically stated, Thurow apparently based his conclusions on principles of physics and mathematics (not independent research), and endorsed the inverse relationship reported by Kamayami and Sasaki. He claimed that narrow brackets allow increased tipping, which causes a progressive increase in the friction-producing forces normal to the archwire and bracket slot, as observed in Kamayami and Sasaki's experiment. Frank and Nikolai, however, held the slot angulation (and, therefore, the normal-force value) constant within each subsample.

Frank and Nikolai (1980), Petersen and coworkers (1982), and Garner, Allai, and Moore (1986) also compared the relative contributions to friction of different wire materials. In all three experiments, using stainless-steel brackets at zero-degrees angulation (bracket-slot and wire parallel), stainless-steel wire exhibited less friction than a nickel-titanium-alloy wire (Nitinol; Unitek Corp., Monrovia, CA.) against the bracket-slot. With increased angulation, however, the Nitinol wire created much less friction than the stainless steel wire. These results reflect the impact on friction of wire flexural stiffness, a parameter dependent on wire cross-sectional size and shape, material, and interbracket distance (Nikolai, 1985). The much lower stiffnesses of the nickel-titanium-alloy wires resulted in lower normal forces at the contacts of wire and bracket-slot and, therefore, less friction. As Frank and Nikolai noted, however, lower stiffness allows greater tipping, and factors other than friction must be considered in determining the ideal bracket-archwire combination for a given clinical situation.

Wet versus Dry Environment

As previously stated, Andreasen and Quevedo (1970) reported that their results were not significantly different, experimenting under conditions of a dry field versus those encountered under saliva lubrication. Additional studies that compared friction under wet and dry conditions have been reported by Koran, Craig, and Tillitson (1972), and by Stannard, Gau, and Hanna (1986). Although not simulating orthodontic mechanics, Koran and associates showed a significant *increase* in the friction generated between two porcelain surfaces using fresh saliva as a lubricant compared to dry conditions. Stannard, Gau, and Hanna pressed two one-inch flat surfaces of stainless steel against orthodontic wires of various materials, and measured friction under wet and dry conditions with increasing normal force. They determined that these surfaces wet with an artificial saliva medium yielded consistently higher coefficients of friction than the same surfaces under dry conditions.

In an experiment designed specifically to measure friction in a simulated orthodontic environment, Baker, Nieberg, Weimer, and Hanna (1987) reported significantly *lower* friction under conditions of saliva-substitute immersion versus a dry environment. All brackets were made of stainless steel and, although not explicitly stated, results suggested that all measurements were made with bracket-slots and wires parallel. The possible impact of relative bracket-slot/archwire angulation on these measurements was not discussed.

New Materials in Orthodontics

Ceramic Materials

Ceramics are generally defined by materials scientists as including all solid materials that are neither metals, alloys, nor polymers (although a ceramic may contain some metallic and polymeric elements as constituents or additives) (Bowen, 1986). Ceramics used in the manufacture of orthodontic brackets are primarily aluminum oxide (Al_2O_3). This means they belong to the "corrundum" family of ceramic products. These ceramics are manufactured by first mixing the fine Al_2O_3 powder with liquid organic-polymer binders, and compacting the resultant mixture to relieve voids. This mixture is then raised to a specific temperature at a controlled rate, a process called "firing", to form a molten alumina mass. During the firing stage, the primary and most critical processes occurring are densification and grain growth. Densification, as the name implies, is the process by which an originally porous material is transformed into a strong, dense entity. Grain growth is the process by which the average grain size of strain-free material increases continuously during heat treatment without change in the grain-size distribution. Control of these two processes is necessary in order to develop the desired properties in the final ceramic product, and is achieved by carefully monitoring the rate of temperature rise, the maximum temperature achieved, and the rate of cooling (Kingery, Bowen, and Uhlman, 1976).

The production of single-crystal versus polycrystalline ceramics is an example of the effect of altering manufacturing variables. Either type of ceramic may be composed of aluminum oxide; however, a much finer powder is required to produce the polycrystalline variety. To produce large, single crystals, the molten alumina must be "fired" to an extremely high temperature under high pressure. The rate of cooling is then carefully controlled to allow growth of a single "seed" crystal into a solid-crystal rod (up to 50 millimeters in length). The resultant rod is then cut, and pieces are milled to achieve the desired final shapes.

Polycrystalline ceramics, as the name implies, are composed of many separate crystals (or grains) that are adjacent to one another at junctions known as grain boundaries. Production of the polycrystalline molten alumina is accomplished at lower temperature and pressure than required for the single-crystal ceramic. This molten mass is converted to the desired shape by 1) injection molding (the molten mass forced into a closed mold), 2) extrusion molding (the mass forced through a die of the desired cross-section), or 3) slip casting (the mass poured into a porous mold that absorbs the excess fluid). The shaped object is then dried and fired a second time at a temperature below that which would cause the ceramic to completely melt: a process called sintering. During the sintering process, most voids between particles are removed, causing shrinkage, and the ceramic particles are "welded" together (Bowen, 1986). Control of this second firing, and subsequent cooling, are critical in regulating the ultimate grain size (important in determining fracture strength and toughness) and pore size and shape (important in obtaining maximum packing density) (Kingery et al., 1976).

The molecular microstructure of ceramics is ultimately responsible for the macroscopic properties observed. Within each grain, ceramics typically have strong ionic-covalent bonds (i.e., a hybrid bonding that is not strictly ionic or covalent). These bonds give ceramics the desirable properties of corrosion resistance, hardness, strength, and stiffness. The lattice structure typical of metallic bonding allows inelastic deformation along "slip planes", a characteristic not generally observed in ceramic compounds. Ceramics will generally exhibit retention of size and shape to a relatively high level of energy input, and suddenly fracture will occur. Metals, however, typically deform inelastically at loads and energies notably below the input levels required to cause rupture. This deformation, known as yielding, results in redistribution of residual stresses along grain boundaries to allow formation of a new, stable lattice structure (Bowen, 1988).

According to Scott (1988), the potential capability to resist fracture (breakage) is the mechanical property that most distinguishes ceramics from metals. The tendency in ceramics toward propagation of cracks along grain boundaries that intersect microscopic defects adversely affects this capability, however. These defects may take the form of voids, chemical impurities, or agglomerations, and may originate during the manufacture of the ceramic material, during the processing of the ceramic (i.e., during fabrication of an orthodontic bracket), or may be introduced in the form of scratches before or during use (Bowen, 1988).

Ceramic Brackets

Orthodontic brackets of aluminum oxide have recently been introduced in both the polycrystalline and single-crystal forms. As described above, manufacturing and processing methods of the two forms are quite different. Polycrystalline brackets are manufactured by molding the mixture of aluminum oxide and binders into shapes from which brackets can be cut after processing. The mass is raised to a high temperature to "burn-out" the binders, and the resultant "blank" is machined to the desired specifications with diamond cutting tools. The bracket is then heat treated to remove surface imperfections and relieve stresses (Swartz, 1988).

Single-crystal brackets, however, are processed from man-made single-crystals, commonly called "sapphires." Orthodontic manufacturers purchase these large crystals, mill them to the desired dimensions (using diamond cutting tools and/or ultrasonic cutting techniques), and heat treat them to relieve stresses and remove any surface imperfections caused by the milling process (Swartz, 1988). In some manufacturing processes, the surface of the crystal may then be bombarded with ions (e.g., titanium ions) to add strength to the bracket (Tuneberg, 1989).

Flores (1988) compared the fracture strengths of several ceramic brackets and yield strengths of stainless steel brackets under loads generated by engaged archwires in torsion, and found "perfect" single-crystal brackets superior to polycrystalline brackets. When scratches were made along the base of the bracket-slot of each bracket, however, the strength of the polycrystalline bracket was not affected, while that of the single-crystal bracket was decreased to about that of the polycrystalline form. Throughout all tests, however, the stainless steel brackets were found superior to both types of ceramic brackets.

Summarily, researchers have observed that the only advantage of ceramic brackets over conventional stainless steel brackets appears to be their superior cosmetic appearance (Kusy, 1988; Scott, 1988).

Teflon-coated Archwires and Ligature-wires

Polytetrafluoroethylene (PTFE), a perfluorinated straight-chain high polymer of the tetrafluoroethylene monomer, is more commonly known by the trade name Teflon (trademark by E.I.duPont de Nemours & Co., Inc., Wilmington, DE). The material in its various forms is highly desirable for numerous industrial and commercial uses by virtue of its high thermal stability, chemical inertness, electrical resistivity, resistance to wear, and low coefficients of friction with other materials. These properties are directly attributable to the chemical structure of fluorine atoms forming a protective sheath over a central chain of carbon atoms. This protective sheath prevents attack by various chemical agents, increases stability, and lowers surface energy (Encyclopedia of Chemical Technology, 1980).

The characteristics of wear resistance and low frictional resistance make Teflon potentially desirable for use as a coating material for certain orthodontic appliances. Teflon exhibits exceptionally low frictional resistance in non-lubricated applications, especially at low surface velocities and pressures higher than 5 lbs/in^2 (Teflon Mechanical Design Data, n.d.). The static coefficient of friction for Teflon against itself or against steel (0.04), for example, is less than $1/10^{th}$ of that for steel against steel (0.58) (CRC Handbook of Chemistry and Physics, 1986).

A decade ago, investigators reported the possibility of coating orthodontic archwires with Teflon (Greenberg and Kusy, 1979). Problems with peeling and cracking, and the inability to apply the coating material as a thin layer were encountered, however, and coated archwires were not made available for commercial use at that time (Whitley, 1989). More recently, improvements in coating procedures have resulted in the marketing of archwires and ligature wires of stainless steel coated with Teflon. These wires are reported to have more-uniform coatings with reduced thicknesses and higher resistances to peeling, cracking, and wear than previously available coated wires (Peterson, 1989). Verification of these claims by independent study has not been reported in the orthodontic literature.

Origin of the Present Research Design

Development of an effective orthodontic force system is dependent upon several factors, one of which may be the management of frictional forces. The magnitudes of these frictional forces are, in turn, dependent on several factors that may be controlled clinically to a certain extent. The orthodontic literature contains considerable documentation on the effects of certain variables on friction, including archwire size and shape, bracket-slot dimensions, relative angulation of the bracket and archwire, and interbracket distance. Experiments have also been undertaken to study frictional forces associated with different materials (including stainless steel and Teflon) in contacting plane surfaces. Comparison of frictional force magnitudes generated by appliances including brackets of single-crystal ceramics, polycrystalline ceramics, or stainless steel, and comparison of frictional forces associated with stainless steel archwires or ligature-wires with and without Teflon as a surface-coating material have not been reported in the literature.

The purpose of the present study was to measure and compare the magnitudes of frictional forces generated within a relevant sample of test specimens during simulated orthodontic edgewise sliding mechanics. Specifically, the null hypotheses tested were:

1) Within subsamples, the magnitudes of maximum static frictional forces generated within test specimens are equal.
2) Within subsamples, the magnitudes of mean kinetic frictional forces generated within test specimens are equal.

Information gained from this investigation should help define the appropriate role and potential limitations of the orthodontic appliance components tested.

CHAPTER THREE

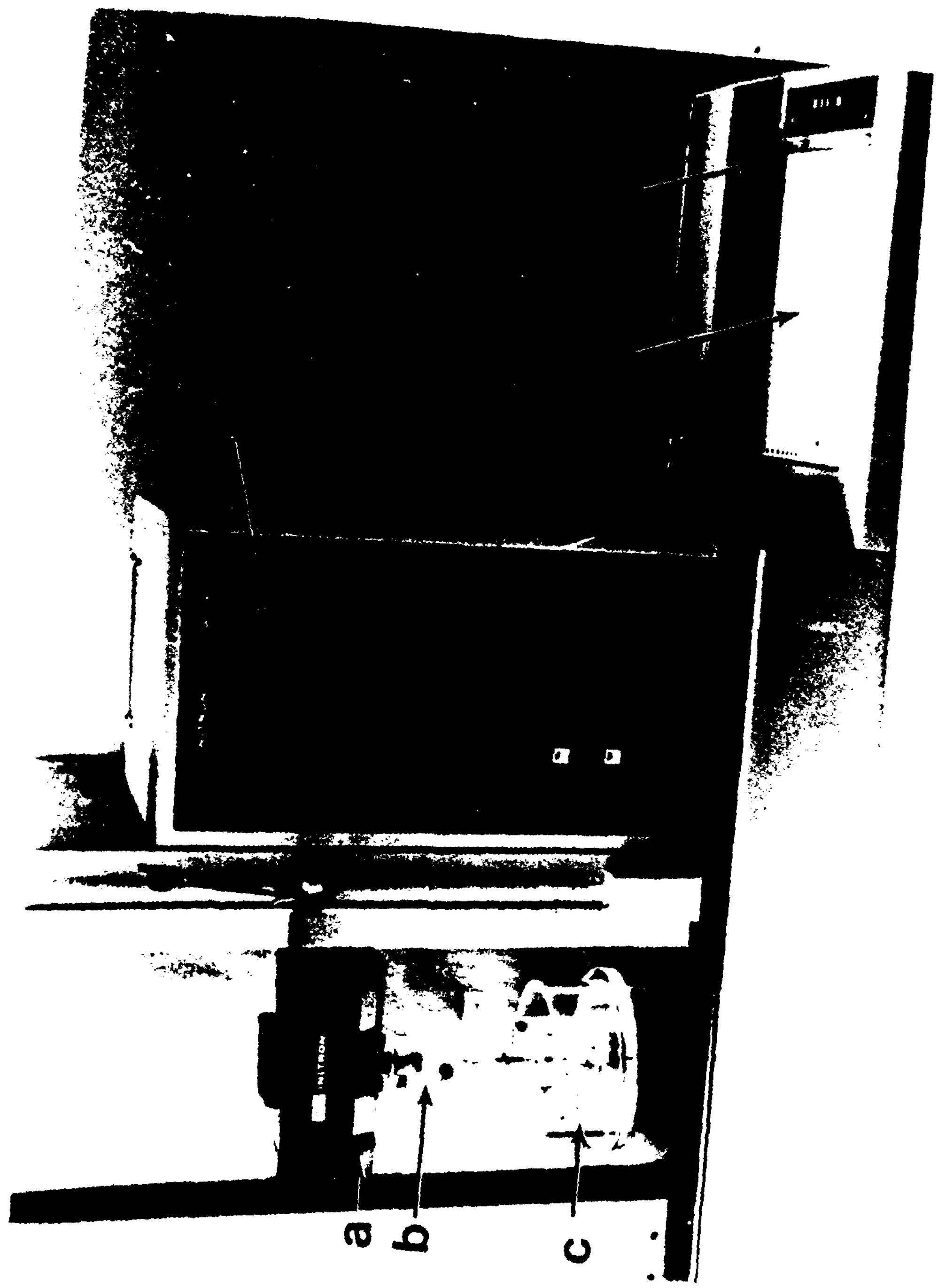
MATERIALS AND METHODS

The objective of this laboratory study was to measure and compare the magnitudes of frictional forces generated within test specimens in a controlled experimental environment; each specimen consisted of an orthodontic bracket, an archwire segment, and ligation. Relative displacement within the specimen confines simulated sliding orthodontic mechanics: movement of a bracket along an archwire (i.e., as in cuspid retraction). This chapter details the apparatus used during testing, the design of the research, preparation for the experiment, a typical test, interpretation of the plot generated, and the reduction of data.

Testing Apparatus

A test fixture, constructed primarily of structural plastic, was designed and fabricated for use with a universal testing machine (Model 1011, Instron Corp., Canton, MA) (Fig. 3-1). The fixture consisted of four principal components: 1) a cylindrical container, 2) a C-frame subassembly, 3) a pedestal subassembly, and 4) an L-frame connector. These four components are described in detail in the following paragraphs and

Fig. 3-1. Universal Testing Machine (Instron Model 1011) displaying the load cell (a) attached to the movable crosshead; standard grip coupling (b); test fixture (c); machine "stop" (d); LCD panel (e); recorder pen (f); and recorder paper (g)


a
b
c

displayed in Figure 3-2.

The primary function of the cylindrical container was to hold the C-frame in a saliva-substitute medium. This fluid was maintained at a level in the cylinder that totally immersed all areas of contact among bracket, archwire, and ligation. The cylinder was rigidly attached to the base grip-coupling of the testing machine.

The C-frame subassembly maintained the archwire segment stationary in vertical alignment. The base of the C-frame held the lower end of the archwire, and was rigidly affixed to the bottom plate of the cylindrical container. The superior arm of the C-frame could be rotated horizontally to allow positioning of the test specimen. This arm supported a small eye-bolt in series with a threaded shaft, a calibrated coiled compression spring (constant = 170 grams/millimeter), and a nut. When the arm was rotated into test position and secured, the eye-bolt engaged an acute bend in the superior end of the archwire segment. In the present experiment, each archwire segment was held, pre-tensioned, in the proper axial alignment. Three full turns of the nut imposed 2.4 millimeters of compressive deformation of the spring, and placed approximately 400 grams of axial tensile force in each archwire segment. This pre-tensioning was intended in part to represent a clinical situation with the archwire "tied back" to a posterior buccal tube crown attachment. Additionally,

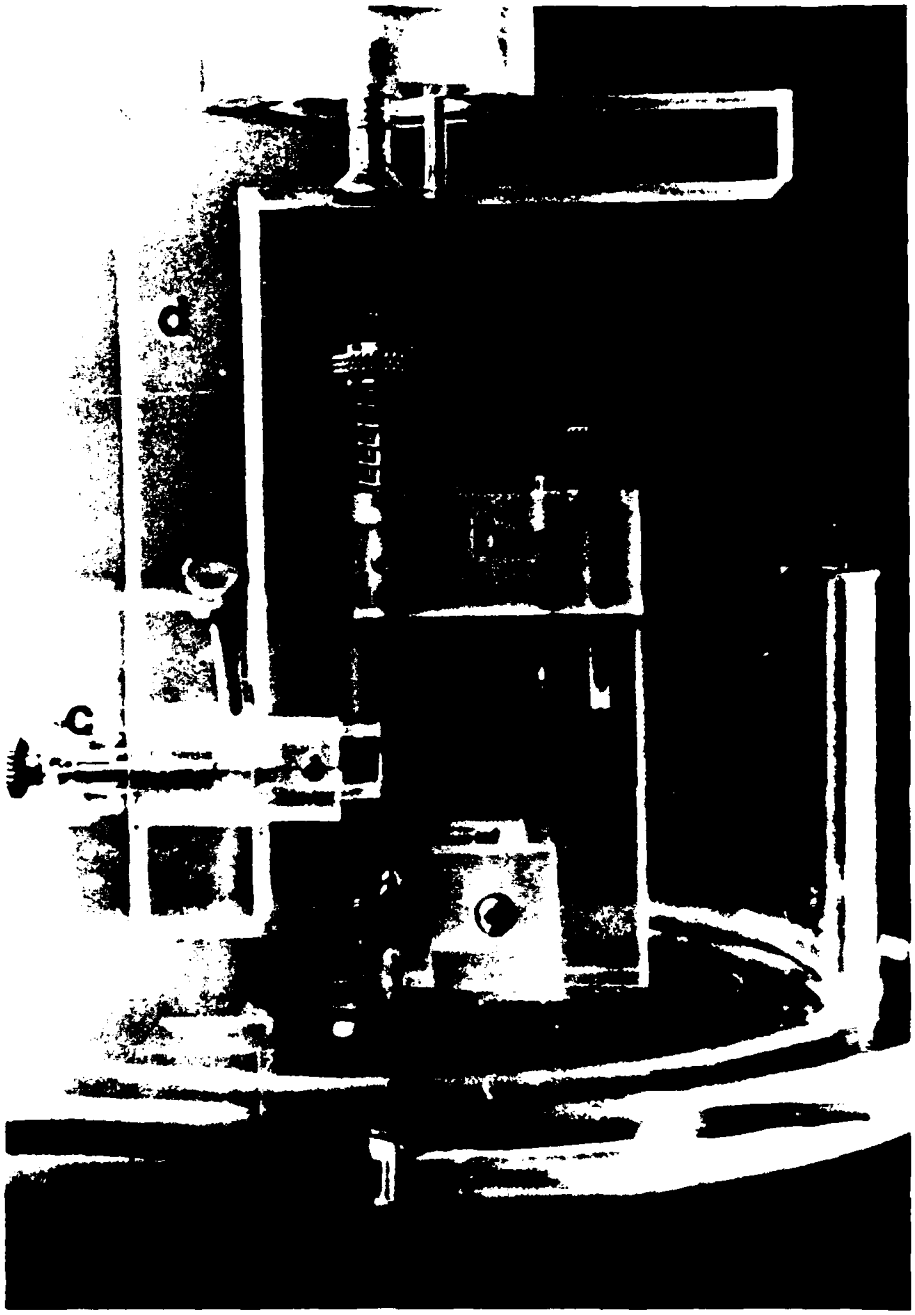


Fig. 3-2. Test fixture with engaged specimen displaying (a) the cylindrical container; (b) the C-frame subassembly; (c) the pedestal sub-assembly; and (d) the L-frame connector.

this tensile force tended to suppress the influence of archwire flexural stiffness on friction during tests.

The purpose of the pedestal subassembly Fig. (3-3) was two-fold: 1) to hold the bracket in the proper position with respect to the archwire segment and 2) to maintain a constant, resultant ligation force on the archwire segment. Each bracket was affixed to an acrylic pedestal that was secured in a plastic sleeve. A pair of ligature-wires, one each at the mesial and distal extents of the bracket, were looped over the engaged archwire segment, and their ends passed through four parallel holes in the acrylic pedestal (Fig. 3-4). Each pair of ligature-wire ends was attached to a closed-coil spring (calibrated at 5.5 grams per millimeter under tension) by "pigtailing" the archwire, and this twisted wire was cut to a length of approximately two millimeters. Opposite ends of these springs were, in turn, attached to wire hooks imbedded in a threaded plastic washer. Prior to each test, the springs were elongated 10 millimeters via a thumbscrew engaging the threaded washer to yield 110 grams of total force delivered faciolingually to the archwire segment.

The purpose of the L-frame was to secure the pedestal subassembly and connect it, through a coupling and the load cell, to the movable crosshead of the testing machine. The pedestal subassembly with attached specimen fit into the vertical arm of the L-

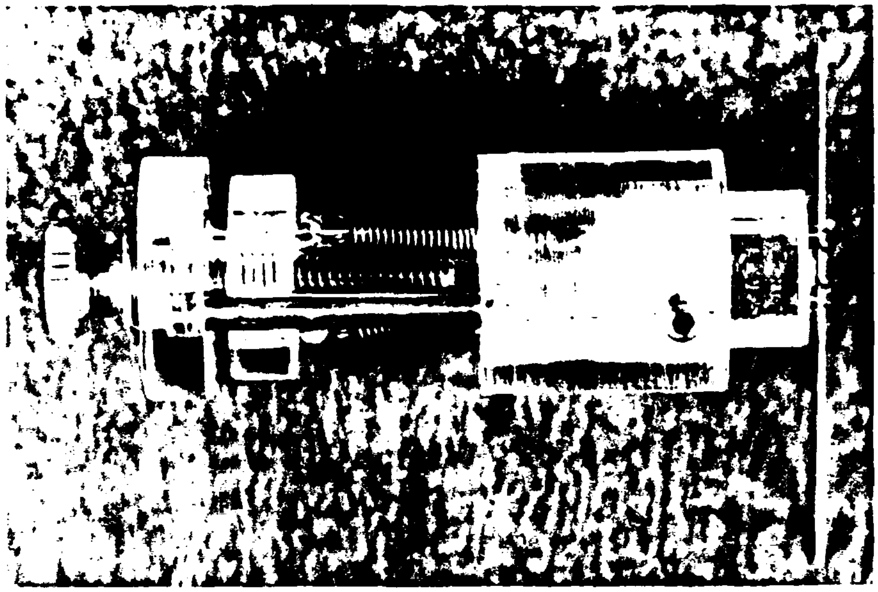


Fig. 3-3. Pedestal subassembly with specimen engaged and coil springs elongated 10 mm.

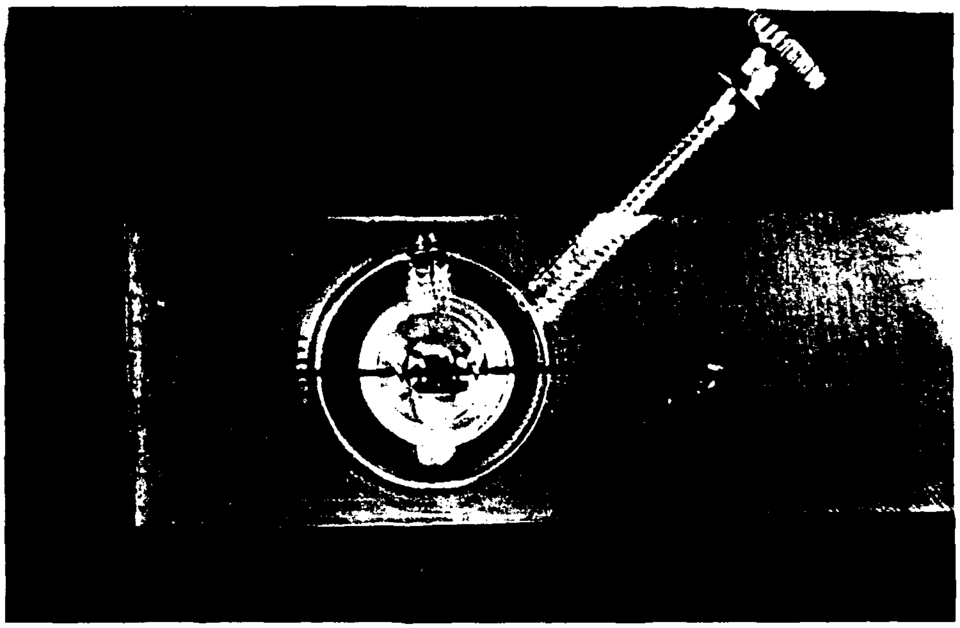


Fig. 3-4. Front view of a specimen engaged at zero-degrees angulation. Position of ligature wires at mesial and distal extents of bracket are evident.

frame. Proper alignment of the ligated archwire segment with the two end-supports in the C-frame subassembly was achieved with an acrylic jig used to set the distance from the lingual surface of the bracket-slot to the L-frame (Fig. 3-5). Bracket-slot angulation (or, simply, angulation), defined as the angle formed between the bracket-slot and the archwire in their pre-engaged configurations, was determined visually by aligning the archwire segment with lines scored at five-degree increments on the L-frame (Fig. 3-4). For tests in this experiment conducted at five degrees angulation, the archwire segment was aligned with the five-degree line on the L-frame with second-order clearance eliminated. This procedure resulted in relative angulation of the *secured* archwire to bracket-slot that was slightly more than five degrees (approximately 1.5 degrees bracket angulation to eliminate second-order clearance plus an additional five degrees to achieve alignment of the archwire segment with the proper line on the L-frame resulted in a total of approximately 6.5 degrees angulation between the bracket-slot and archwire). This procedure was determined during pilot testing to be more accurately reproducible among test specimens than visually aligning the bracket-slot or attempting to maintain the archwire segment parallel with the bracket-slot during alignment.

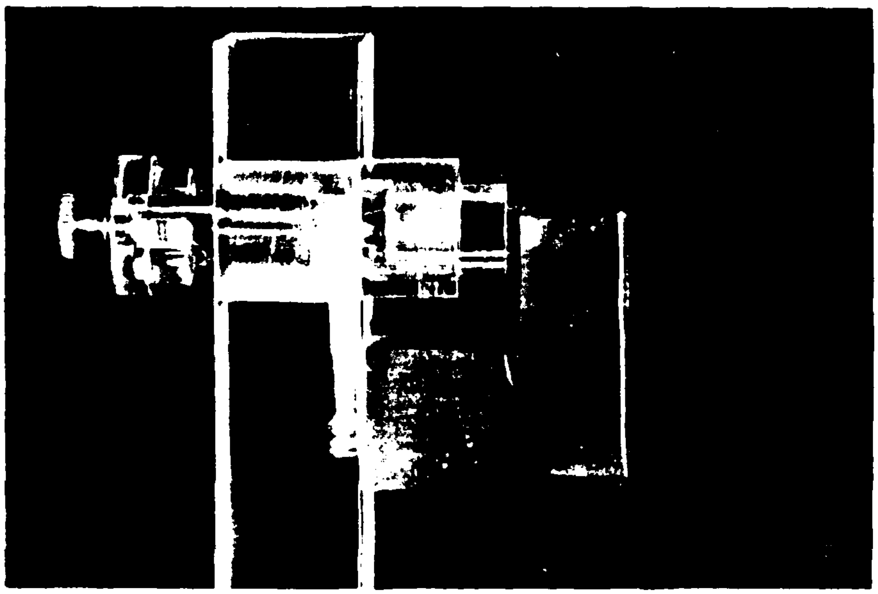


Fig. 3-5. Acrylic Jig in Position.

Research Design

Independent variables examined in this study were bracket (stainless steel, solid-crystal aluminum oxide, and polycrystalline aluminum oxide), archwire (solid stainless steel and stainless steel coated with Teflon), and ligation (also solid stainless steel and stainless-steel ligature wires coated with Teflon). The research project was designed to isolate the effects of these variables on friction. Toward that end, steps were taken to control other parameters generally considered to influence friction in a bracket-wire system. Clinical variables held "constant" during the testing procedure were the following:

1) Length of Archwire Segment: Each archwire segment measured 27 millimeters from the point where it entered the hole in the base of the C-frame to the point where it engaged the eye-hook support. (See "Testing Apparatus.")
2) Diameter of Archwire Segment: Archwire segments were each nominally 0.018 inches (0.457 millimeters) in diameter as received from the vendors.
3) Diameter of Ligature-wires: Ligature-wires were nominally 0.012 inches (0.305 millimeters) in diameter as received from the vendors.

4) Mesiodistal Bracket-Slot Dimension: Selection of brackets in part was based on the desire for alike mesiodistal bracket-slot dimensions. Measurements from a random sample of eight of each of the three brackets with a dial caliper determined the average mesiodistal dimension of each bracket (Table 3-1).

5) Occlusogingival Bracket-Slot Dimension: All bracket-slots were nominally 0.022 inches (0.559 millimeters) measured occlusogingivally as received from the vendors.

6) Initial "Interbracket Distance": "Free lengths" from the mesial and distal extents of each bracket to the supports holding the archwire segment were constants. Repeatability of this initial bracket position for all test specimens was assured by lowering the movable arm of the testing machine to a fixed "stop" prior to each test (Fig. 3-1).

7) Ligation Force: The force of the ligature wires against the archwire specimen was controlled via attachment of the ligature wires to calibrated tension springs. (See "Test Apparatus.")

8) Simulated Intra-oral Environment: All tests were conducted with the specimens immersed in Xero-Lub (Scherer Laborator-

Table 3-1

SPECIMEN MATERIALS

BRACKET

Vendor	Trade Name	Material	Mesiodistal Slot Dimension
ORMCO, A Division of Sybron Corp., Glendora, CA	Twin Mini-Diamond	Stainless Steel	0.156 in. (3.96 mm.)
ORMCO	GEM	Single Crystal Al_2O_3	0.151 in. (3.84 mm.)
GAC Corp., Central Islip, NY	Allure	Polycrystalline Al_2O_3	0.154 in. (3.91 mm.)

ARCHWIRE

Vendor	Trade Name	Material	Diameter
GAC Corp., Central Islip, NY	Accuform	Coated Stainless Steel	0.018 in. (0.46 mm.)
Unitek Corp./3M, Monrovia, CA	Standard Round Wire	Stainless Steel	0.018 in. (0.46 mm.)

LIGATURE WIRE

Vendor	Trade Name	Material	Diameter
GAC Corp., Central Islip, NY	Teflon Coated Ligature Wires	Coated Stainless Steel	0.012 in. (0.30 mm.)
Unitek Corp./3M Monrovia, CA		"Dead-soft" Stainless Steel	0.012 in. (0.30 mm.)

ies, Dallas, TX), a commercially-available saliva substitute medium.

In addition to the above "constants", angulation was the same within each primary subsample (zero or five degrees, as described). All test specimens were composed of representative brackets and wires obtained without bias directly from vendors of orthodontic supplies (Table 3-1).

Dependent variables quantified were the maximum static frictional force (the force required to initiate movement of the bracket relative to the archwire) and the mean kinetic frictional force (the average frictional force generated during movement of the bracket along the archwire segment). A total of 144 bracket-archwire-ligation specimens were tested: six repetitions of each combination of independent-variable values (3 X 2 X 2), within each of the two primary subsamples. This number of repetitions was estimated to produce sufficient raw data in the present controlled environment to yield interpretable statistical outcomes from the test results. Individual-specimen tests were ordered with respect to angulation and archwire, and randomized with respect to bracket and ligation. Individual brackets, archwires, and ligature wires were used for only one test.

Preparation for Testing

Brackets were bonded to the acrylic pedestals with a composite resin (System 1+, ORMCO, Glendora, CA) in subsets of 18 (dictated by the number of pedestals available). Each bracket was centered between two sets of holes designed to guide the ligature wires, with the bracket-slot oriented perpendicular to these sets. Each subset consisted of six each of the three brackets differing by material (Fig. 3-6). Blind drawings of colored marbles prior to each test determined the testing order of brackets and ligature-wires.

All archwire and ligature-wire segments were prepared prior to testing, and were drawn randomly from the total sample at the time of testing. Ligature-wires were prepared as straight 80 millimeter segments, and looped over the archwire during specimen assembly. Stainless steel archwire segments were prepared from as-received straight "sticks" of wire; coated archwire segments were prepared from the straight posterior portions of preformed archwires.

The testing machine was calibrated in accordance with manufacturer's instructions prior to the initiation of testing, and checked following the completion of alternate subsets (after 36, 72, 108, and 144 tests).

Pilot testing was conducted to 1) determine the appropriate settings for the testing machine, 2) familiarize the operator with the testing apparatus, and 3) determine the order of steps during assembly of the test specimen. Forces generated during these preliminary tests were substantially less than 500 grams,

Fig. 3-6. Pedestals with representative brackets affixed (from left to right): stainless steel, single-crystal ceramic, and polycrystalline ceramic.

permitting the use of the most sensitive load-scale setting (500 grams). The slowest crosshead speed (1 millimeter per minute) was used to most accurately simulate tooth movement. A chart paper speed of 50 millimeters per minute produced plots with a magnification ratio of 50. A minimum of 1.1 millimeters of crosshead movement ("mesiodistal" bracket displacement) during each test resulted in plots at least 55 millimeters in length. This length allowed comparison of the overall plot "pattern" among specimens and generated an adequately large plot to enable calculation of the mean kinetic frictional force (see sample data sheet, Fig. 3-7).

Noted during pilot testing was the "buoyancy effect" of the saliva-substitute on the immersed specimen. As a result of this finding, the machine load-cell was "zeroed" prior to each testing sequence *after* the assembled specimen had been lowered to the level at which testing would start, and *before* engagement of the archwire segment in the C-frame.

A Typical Test

A typical test sequence commenced after the appropriate previously-prepared bracket (affixed to a pedestal), archwire segment, and ligature-wire segments were randomly selected. To assemble the specimen, the L-frame was uncoupled from the crosshead of the testing machine, and the pedestal subassembly was removed from the frame. Placement of the specimen and completion of

Specimen No. ______ Test Date: ___/___/___

INDEPENDENT VARIABLES

Bracket Material: [ ] St Steel [ ] SC Ceramic [ ] PCC

Arch-wire Material: [ ] Stainless Steel [ ] PTFE

Ligation Material: [ ] Stainless Steel [ ] PTFE

Angulation: [ ] Zero degrees [ ] Five degrees

INSTRUMENTATION SETTINGS

Load Scale = 500 grams Crosshead Speed = One mm/min

Chart-paper Speed = 50 mm/min Magnification Ratio = 50.

DEPENDENT VARIABLES

Maximum (Static) Frictional Force (Peak 1 Load) = ______ grams

Kinetic Frictional Force Values (in grams): ______________,

______________, ______________, ______________,

______________, ______________, ______________,

______________.

Mean Kinetic Frictional Force = ______ grams

REMARKS ABOUT THIS TEST: ______________________________,

____,

____.

(This Space for Attachment of Recorder Plot, Specimen)

Thesis Research of Dr. James Gill 1989

Fig. 3-7. Sample data sheet.

the test procedure involved the following steps:

1) The archwire was inserted into the bracket slot, two ligature wires were looped over the wire and their ends passed through the holes in the pedestals.
2) At the base of the pedestal, each pair of ends of the two ligature wires was secured to one end of a coiled tension spring. Care was taken that no force was yet delivered to the archwire segment by the ligature wires; at this stage of assembly, the wire specimen should slide freely within the bracket slot.
3) The pedestal was secured in the plastic sleeve with the two springs passing through the center of the sleeve.
4) The ends of the two springs that were not secured to the ligature wires were attached to the plastic washer and placed in controlled tension, creating the resultant ligation force (110 grams).
5) The pedestal subassembly was secured in the L-frame. Position of the bracket and angulation of the archwire were fixed.
6) The L-frame was re-attached, and the crosshead was lowered to the initial position; the specimen was now totally immersed in the artificial saliva medium.

7) The load reading on the LCD panel of the testing machine was set to zero.

8) The inferior end of the archwire segment was secured in the C-frame base.

9) The superior arm of the C-frame, initially rotated out of the testing plane, was rotated into position so that the eye-bolt engaged the upper, bent end of the archwire. This arm was then secured.

10) The spring through which the eye-bolt passes was compressed 2.4 millimeters (three full turns of the nut), placing approximately 400 grams tension in the archwire.

11) The C-frame was lightly tapped to relieve any "friction-lock" created during final engagement of the wire segment.

12) The recorder was started, and the testing machine was subsequently activated, delivering force in an upward direction to the bracket. When the crosshead displacement (and therefore bracket displacement) exceeded 1.1 millimeters (as read on the LCD panel of the testing machine), both recorder and machine were shut off.

13) Bracket and archwire segments from each test were saved in appropriately labeled envelopes.

Plot Interpretation

Plots were examined in numerical sequence after all 144 tests had been completed. Maximum static frictional force was recorded as the force attained when the initial slope (nearly vertical) first decreased in value (where the plot first peaked or exhibited a slope discontinuity) (Fig. 3-8). The mean kinetic frictional force for a specimen was defined as the average of eight discrete values recorded during relative displacement of bracket and archwire segment. These readings were taken at evenly-spaced intervals on the chart paper; each interval represented 0.127 millimeters (0.005 inches) of actual bracket displacement. All force measurements were recorded to the nearest gram.

In addition to the quantitative values recorded, each plot was studied individually and in relation to other plots from various subsamples to discern any general patterns or characteristics present. Brackets and archwires were examined under 50X magnification using a binocular microscope (American Optics, Buffalo, NY).

Data Reduction

Analyses of variance of maximum static and mean kinetic frictional forces were performed on a Leading Edge, Model D computer (Leading Edge Corp., Canton, MA) using a commercially available statistics software package, "SYSTAT" (Systat, Inc., Evanston, IL). Tukey's "Honestly Significant Difference" (HSD) post-hoc

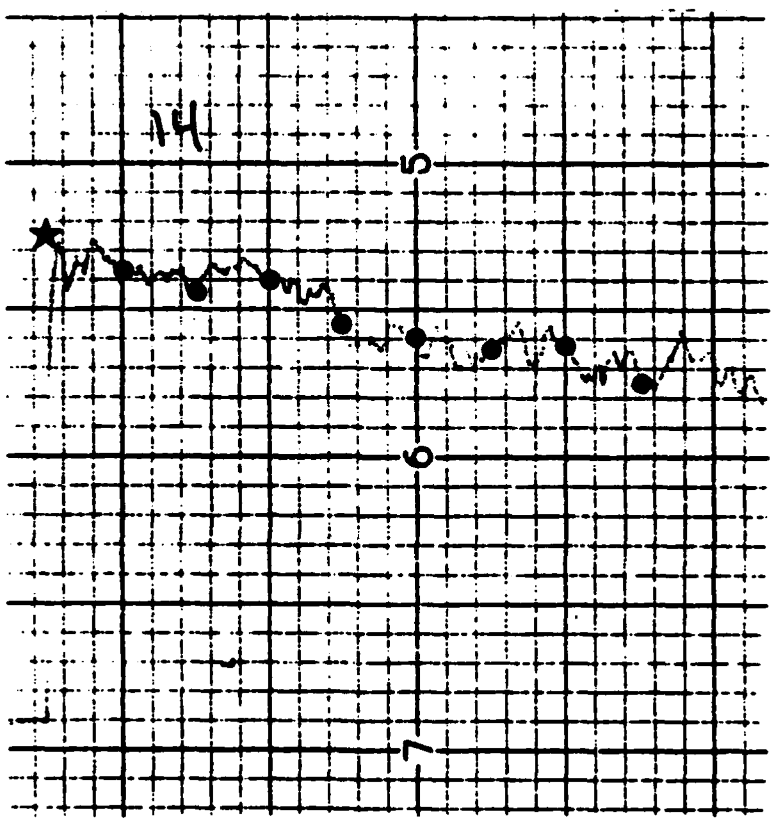


Fig. 3-8. Sample test plot with the maximum static frictional force (★) and eight discrete points (●) used to determine the mean kinetic frictional force demonstrated.

test was conducted as necessary to determine statistically significant differences between subsample means (Kirk, 1968).

CHAPTER FOUR

RESULTS

Reduced data from the experiment consisted of two dependent-variable values associated with each test specimen: the maximum static frictional force and the mean kinetic frictional force, each recorded to the nearest gram. To evaluate the effects of the independent variables on these data, a total of four analyses of variance were performed: one analysis on each of two subsets of dependent-variable data obtained from each of the two primary subsamples (defined by zero and five degrees angulation). Within each primary subsample, all combinations of the selected independent-variable values were included in a 3 X 2 X 2 format (three brackets by two archwires by two ligature-wires).

The analysis-of-variance summary tables in this chapter give the F-ratios and "P" values associated with the three independent variables individually and in all combinations. For this experiment, a statistically significant influence on the dependent variable was considered to be one that would have occurred by chance in less than five of every one hundred observations ($P < 0.05$). When an independent variable with greater than one degree of freedom (more than two values included in the research design) showed a significant main-effect influence (as indicated by $P < 0.05$), or when a significant interaction was indicated between two independent variables, a table of means was included and Tukey's Honestly Significant Difference (HSD) post-hoc test was carried out. This test, also performed for each table of cell means (each subsample partitioned by bracket, archwire, and ligature-wire), enabled pairwise comparisons of individual means (Kirk, 1968).

Within each primary subsample, the order of tables presented in this chapter is as follows: 1) the analysis-of-variance summary with maximum static frictional force as the dependent variable (Tables 4-1 and 4-8); 2) the corresponding table of means with subsample partitioned by bracket; 3) the table of means with subsample partitioned by bracket and archwire, and 4) the table of cell means.

The analysis-of-variance summary with mean kinetic frictional force as the dependent variable is presented next (Tables 4-5 and 4-12). Likewise, the summary table is followed by 1) the table of means with subsample partitioned by bracket, 2) the table of means with subsample partitioned by bracket and archwire (five-degrees subsample only), and 3) the table of cell means. (Note: the subsample with tests conducted at zero degrees revealed no significant interactions between brackets and archwires; therefore, a table of means partitioned by bracket and archwire was not indicated).

Following the tables, samples of plots prepared by the recorder during individual tests are presented (Figs. 4-1 and 4-2). These plots were generated during testing of the bracket/archwire/ligature-wire specimens indicated, and are representative of different plot patterns observed.

Table 4-1

ANALYSIS-OF-VARIANCE SUMMARY WITH MAXIMUM STATIC FRICTIONAL FORCE AS THE DEPENDENT VARIABLE: TESTS CONDUCTED AT ZERO-DEGREES ANGULATION

Source	Sum-of-Squares	df	Mean-Square	F-Ratio	P
Bracket (Bkt)	60,100	2	30,100	54.8	0.000
Archwire (AW)	6,900	1	6,900	12.6	0.001
Ligature (Lig)	2,300	1	2,300	4.19	0.045
Bkt X AW	7,960	2	3,980	7.26	0.002
Bkt X Lig	2,050	2	1,020	1.87	0.164
AW X Lig	224	1	224	0.41	0.525
Bkt X AW X Lig	2,430	2	1,220	2.22	0.118
Error	32,900	60	549		
Total	115,000	71	46,300		

Table 4-2

MEAN VALUES OF MAXIMUM STATIC FRICTIONAL FORCE IN GRAMS

FROM TESTS CONDUCTED AT ZERO-DEGREES ANGULATION:

SUBSAMPLE PARTITIONED BY

BRACKET MATERIAL

Tukey's HSD = 16.3 grams

Bracket Material	Force
Stainless Steel	33.0
Single-Crystal Al_2O_3	34.8
Polycrystalline Al_2O_3	95.2

Table 4-3

MEAN VALUES OF MAXIMUM STATIC FRICTIONAL FORCE IN GRAMS
FROM TESTS CONDUCTED AT ZERO-DEGREES ANGULATION:
SUBSAMPLE PARTITIONED BY BRACKET
AND ARCHWIRE MATERIALS

Tukey's HSD = 28.1 grams

Bracket Material	Archwire	
	Uncoated	Coated
Stainless Steel	29.2	36.9
Single-Crystal Al_2O_3	46.3	23.2
Polycrystalline Al_2O_3	116.9	73.5

Table 4-4

MEAN VALUES OF MAXIMUM STATIC FRICTIONAL FORCE IN GRAMS FROM TESTS CONDUCTED AT ZERO-DEGREES ANGULATION: SUBSAMPLE PARTITIONED BY BRACKET, ARCHWIRE, AND LIGATURE-WIRE MATERIALS

Tukey's HSD = 46.0 grams

Archwire Material	Ligature-Wire Material	Bracket: Stainless Steel	Bracket: Solid Crystal	Bracket: Poly-crystalline
Uncoated	Uncoated	31.7	69.2	113.7
	Coated	26.7	23.5	120.0
Coated	Uncoated	41.7	26.3	77.3
	Coated	32.2	20.2	69.7

Table 4-5

ANALYSIS-OF-VARIANCE SUMMARY WITH MEAN KINETIC FRICTIONAL FORCE AS THE DEPENDENT VARIABLE: TESTS CONDUCTED AT ZERO-DEGREES ANGULATION

Source	Sum-of-Squares	df	Mean-Square	F-Ratio	P
Bracket (Bkt)	34,900	2	17,500	35.2	0.000
Archwire (AW)	1,280	1	1,280	2.57	0.114
Ligature (Lig)	3,680	1	3,680	7.42	0.008
Bkt X AW	1,500	2	749	1.51	0.230
Bkt X Lig	1,900	2	951	1.91	0.156
AW X Lig	496	1	496	1.00	0.322
Bkt X AW X Lig	1,540	2	770	1.55	0.220
Error	29,800	60	496		
Total	75,100	71	25,900		

Table 4-6

MEAN VALUES OF MEAN KINETIC FRICTIONAL FORCE IN GRAMS FROM TESTS CONDUCTED AT ZERO-DEGREES ANGULATION: SUBSAMPLE PARTITIONED BY BRACKET MATERIAL

Tukey's HSD = 15.5 grams

Bracket Material	Force
Stainless Steel	37.4
Single-Crystal Al_2O_3	41.1
Polycrystalline Al_2O_3	85.9

Table 4-7

MEAN VALUES OF MEAN KINETIC FRICTIONAL FORCE IN GRAMS FROM TESTS CONDUCTED AT ZERO-DEGREES ANGULATION: SUBSAMPLE PARTITIONED BY BRACKET, ARCHWIRE, AND LIGATURE-WIRE MATERIALS

Tukey's HSD = 43.8 grams

		Bracket		
Archwire Material	Ligature-Wire Material	Stainless Steel	Solid Crystal	Poly-crystalline
Uncoated	Uncoated	36.7	73.0	96.7
	Coated	34.0	26.3	87.3
Coated	Uncoated	42.2	37.5	85.7
	Coated	36.8	27.5	73.8

Table 4-8

ANALYSIS-OF-VARIANCE SUMMARY WITH MAXIMUM STATIC FRICTIONAL FORCE AS THE DEPENDENT VARIABLE: TESTS CONDUCTED AT FIVE-DEGREES ANGULATION

Source	Sum-of-Squares	df	Mean-Square	F-Ratio	P
Bracket (Bkt)	97,000	2	48,500	62.6	0.000
Archwire (AW)	51,400	1	51,400	66.3	0.000
Ligature (Lig)	618	1	618	0.80	0.375
Bkt X AW	35,000	2	17,500	22.6	0.000
Bkt X Lig	124	2	62	0.08	0.923
AW X Lig	387	1	387	0.50	0.482
Bkt X AW X Lig	371	2	186	0.24	0.788
Error	47,500	60	775		
Total	231,000	71	119,000		

Table 4-9

MEAN VALUES OF MAXIMUM STATIC FRICTIONAL FORCE IN GRAMS FROM TESTS CONDUCTED AT FIVE-DEGREES ANGULATION: SUBSAMPLE PARTITIONED BY BRACKET MATERIAL

Tukey's HSD = 19.3 grams

Bracket Material	Force
Stainless Steel	34.0
Single-Crystal Al_2O_3	48.7
Polycrystalline Al_2O_3	118.2

Table 4-10

MEAN VALUES OF MAXIMUM STATIC FRICTIONAL FORCE IN GRAMS FROM TESTS CONDUCTED AT FIVE-DEGREES ANGULATION: SUBSAMPLE PARTITIONED BY BRACKET AND ARCHWIRE MATERIALS

Tukey's HSD = 33.4 grams

Bracket Material	Archwire	
	Uncoated	Coated
Stainless Steel	34.7	33.3
Single-Crystal Al_2O_3	73.6	23.8
Polycrystalline Al_2O_3	172.7	63.6

Table 4-11

MEAN VALUES OF MAXIMUM STATIC FRICTIONAL FORCE IN GRAMS FROM TESTS CONDUCTED AT FIVE-DEGREES ANGULATION: SUBSAMPLE PARTITIONED BY BRACKET, ARCHWIRE, AND LIGATURE-WIRE MATERIALS

Tukey's HSD = 54.7 grams

		Bracket		
Archwire Material	Ligature-Wire Material	Stainless Steel	Solid Crystal	Poly-crystalline
Uncoated	Uncoated	32.2	72.5	178.2
	Coated	37.2	74.7	167.3
Coated	Uncoated	40.5	28.3	67.7
	Coated	26.2	19.3	59.5

Table 4-12

ANALYSIS-OF-VARIANCE SUMMARY WITH MEAN KINETIC FRICTIONAL FORCE AS THE DEPENDENT VARIABLE: TESTS CONDUCTED AT FIVE-DEGREES ANGULATION

Source	Sum-of-Squares	df	Mean-Square	F-Ratio	P
Bracket (Bkt)	107,000	2	53,300	48.7	0.000
Archwire (AW)	20,600	1	20,600	18.8	0.000
Ligature (Lig)	268	1	268	0.25	0.622
Bkt X AW	12,400	2	6,220	5.68	0.006
Bkt X Lig	3,060	2	1,530	1.40	0.256
AW X Lig	3,190	1	3,190	2.91	0.093
Bkt X AW X Lig	830	2	415	0.38	0.686
Error	65,700	60	1100		
Total	213,000	71	86,600		

Table 4-13

MEAN VALUES OF MEAN KINETIC FRICTIONAL FORCE IN GRAMS

FROM TESTS CONDUCTED AT FIVE-DEGREES ANGULATION:

SUBSAMPLE PARTITIONED BY

BRACKET MATERIAL

Tukey's HSD = 23.0 grams

Bracket Material	Force
Stainless Steel	54.1
Single-Crystal Al_2O_3	67.3
Polycrystalline Al_2O_3	141.5

Table 4-14

MEAN VALUES OF MEAN KINETIC FRICTIONAL FORCE IN GRAMS FROM TESTS CONDUCTED AT FIVE-DEGREES ANGULATION: SUBSAMPLE PARTITIONED BY BRACKET AND ARCHWIRE MATERIALS

Tukey's HSD = 39.7 grams

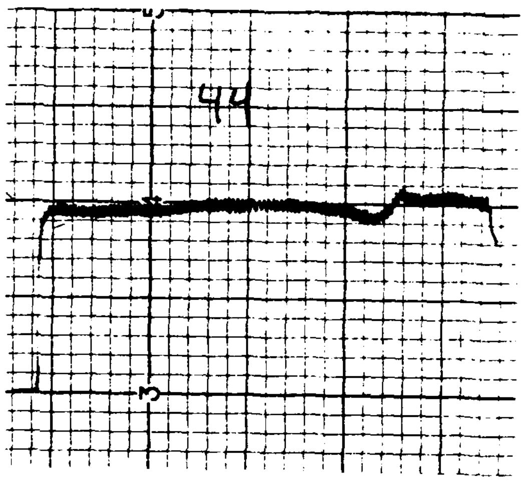
Bracket Material	Archwire	
	Uncoated	Coated
Stainless Steel	54.1	54.1
Single-Crystal Al_2O_3	86.0	48.7
Polycrystalline Al_2O_3	173.6	109.5

Table 4-15

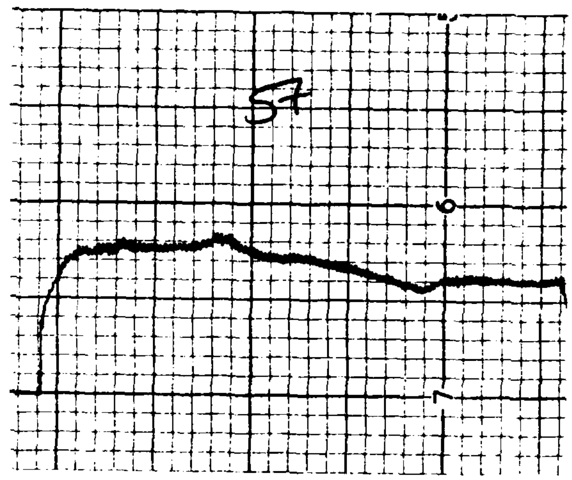
MEAN VALUES OF MEAN KINETIC FRICTIONAL FORCE IN GRAMS FROM TESTS CONDUCTED AT FIVE-DEGREES ANGULATION: SUBSAMPLE PARTITIONED BY BRACKET, ARCHWIRE, AND LIGATURE-WIRE MATERIALS

Tukey's HSD = 65.0 grams

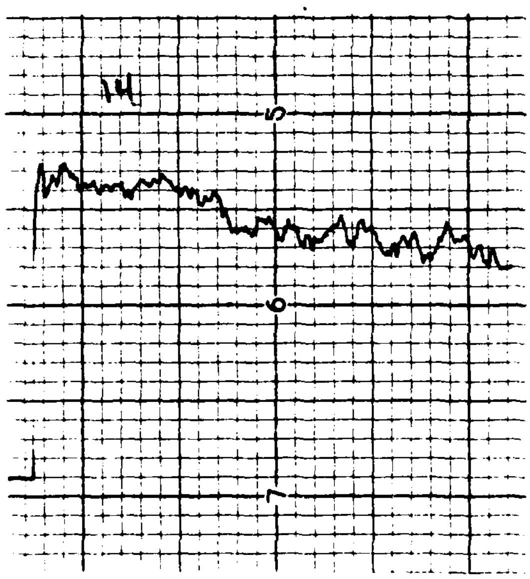
		Bracket		
Archwire Material	Ligature-Wire Material	Stainless Steel	Solid Crystal	Poly-crystalline
Uncoated	Uncoated	48.5	77.8	173.2
	Coated	59.7	94.2	174.0
Coated	Uncoated	63.3	44.8	129.8
	Coated	44.8	52.5	89.2



A.

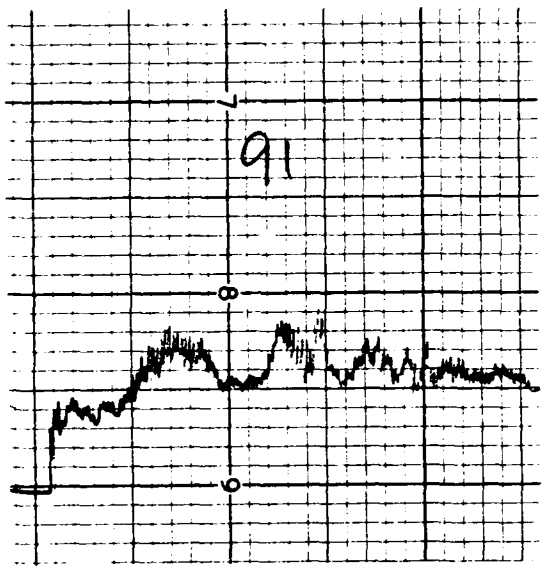


B.

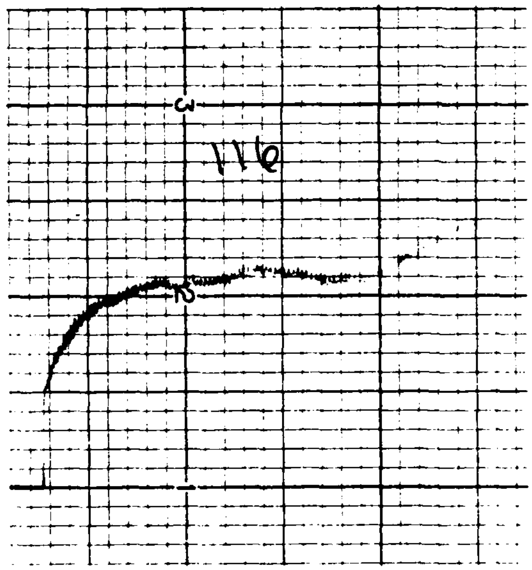


C.

Fig. 4-1. Representative plots from tests at zero-degrees angulation. Specimens consisted of (A) a stainless steel bracket, coated archwire, and uncoated ligation; (B) a single-crystal bracket, coated archwire, and coated ligation; and (C) a polycrystalline bracket, uncoated archwire, and coated ligation.



A.



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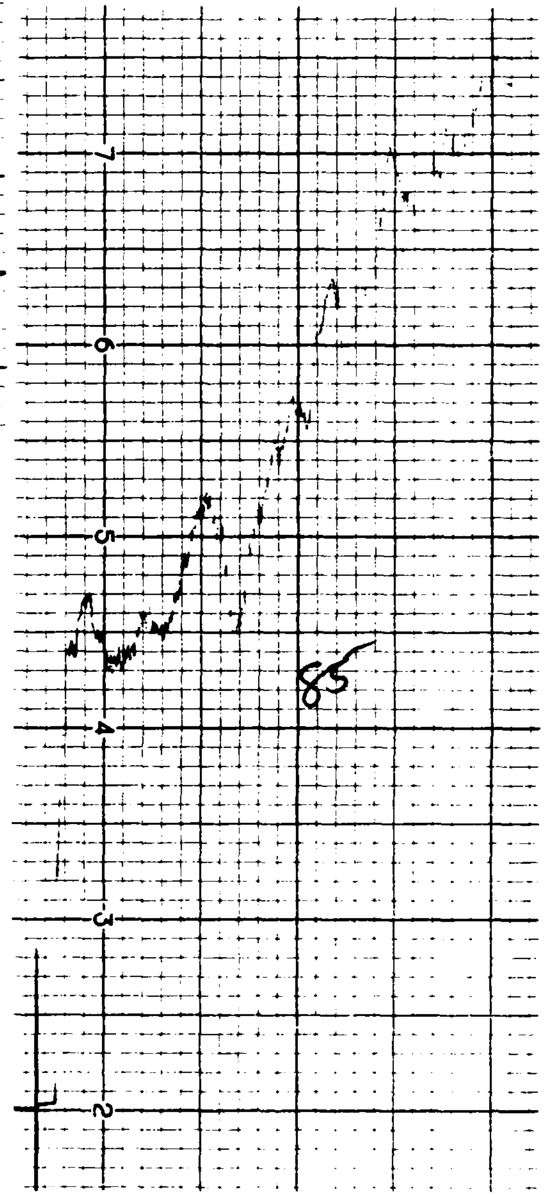

C.

Fig. 4-2. Representative plots from tests at five-degrees angulation. Specimens consisted of (A) a stainless-steel bracket, uncoated archwire, and uncoated ligation; (B) a single-crystal bracket, coated archwire, and coated ligation; and (C) a polycrystalline bracket, uncoated archwire, and coated ligation.

CHAPTER FIVE

DISCUSSION

The objective of this study was to measure and compare frictional forces generated in a controlled experiment simulating orthodontic edgewise sliding mechanics. Each test specimen consisted of an orthodontic bracket (stainless steel, single-crystal ceramic, or polycrystalline ceramic), an archwire segment (uncoated stainless steel or a stainless-steel core coated with Teflon), and ligation (ligature wires of uncoated or Teflon-coated stainless steel). This chapter highlights notable findings from the statistical analyses of the data, and attempts to interpret those outcomes. To facilitate these interpretations, the chapter is organized under the following main topics:

1) review of orthodontic friction;
2) interpretations of experimental results;
3) comparison with previous studies;
4) clinical relevance of the present study; and
5) suggestions for further research.

Review of Orthodontic Friction

Friction is created when two contacting surfaces slide or attempt to slide with respect to one another, impeding relative displacement. The magnitude of the frictional force is influenced by the nature of the contacting surfaces and the action-reaction normal forces (components perpendicular to the contact plane) exerted on the contacting areas. Controlled experimentation with contacting plane surfaces ("flats") has shown that "maximum friction and the level of frictional force following the initiation of motion are highly dependent on the relative roughness of the contacting surfaces..." (Nikolai, 1985). Although not proven, a similar correlation between archwire and/or bracket-slot surface roughnesses and friction during orthodontic sliding mechanics is suspected (Kusy et al., 1988).

Contact relationships between archwire, bracket-slot, and ligation affect the level of frictional resistance during sliding orthodontic mechanics. Viewed from the facial perspective (Fig. 2-1), contact between an archwire and bracket-slot may exist in one of three formats, depending upon the dimensions of wire and slot and their relative angulation. The magnitudes of the normal forces are greater in the absence than in the presence of second-order clearance, and are directly related to the angulation between the archwire and bracket-slot in their passive configurations. Increased normal-force magnitudes at diagonally-opposite slot edges caused by increased angulation, in turn, cause greater frictional resistance to movement (Frank and Nikolai, 1980).

From an occlusal perspective, normal forces are generated between archwires and brackets along the facial surface or an edge of the bracket-slot, and between archwires and ligation (Fig. 2-2). Each of the normal-force components in the spatial analysis contributes to the total frictional resistance in a bracket/archwire/ligation system (Frank and Nikolai, 1980).

Two related forms of sliding friction are important in orthodontic mechanics: static (before motion) and dynamic (or kinetic, during motion) (Nikolai, 1985). The resistive force that must be overcome by the action to initiate motion is termed the maximum static frictional force (Frank and Nikolai, 1980). Following the initiation of movement, friction continues to oppose the motion (kinetic frictional force), but often at a level slightly below the maximum (Beer and Johnston, 1984).

Interpretation of Experimental Results

Within each subsample, kinetic and maximum static frictional forces were examined individually and with respect to one another. Results from tests conducted at zero-degrees angulation are considered first. With the wire and slot parallel as viewed from the facial perspective, the contact resembles that of the classic block-on-plane frictional force model. Results from the tests conducted at five-degrees angulation, creating two-point contacts between the round archwire and slot edges, are discussed in a similar fashion. Next, trends observed during evaluation of the test results are discussed, including static forces versus kinetic forces and forces generated at zero-degrees versus five-degrees angulation. Finally, an evaluation of plot patterns is presented.

Frictional Forces from Tests at Zero Degrees Angulation

Evaluation of Maximum Static Frictional Force

The analysis-of-variance summary with maximum static frictional force as the dependent variable (Table 4-1) indicated significant main-effect influences from bracket, archwire, and ligature wire. Overall, polycrystalline brackets were associated with significantly higher average maximum static frictional force values than the statistically equal values for the stainless-steel- and single-crystal bracket subsamples. Uncoated archwires were associated with overall larger frictional forces than coated archwires.

Slot surfaces of polycrystalline brackets examined under 50X magnification appeared to have a coarser surface texture and more prominent surface irregularities than slot surfaces of the stainless-steel or single-crystal brackets. This observation supports the outcome of higher force values associated with polycrystalline brackets and concurs with the report by Kusy (1988) of greater surface roughnesses associated with polycrystalline bracket-slots compared to stainless-steel slots, as measured by laser spectroscopy. The larger frictional forces associated with uncoated ligature wires are attributable to the lower coefficients of static friction for Teflon against stainless steel or against Teflon compared to that between stainless steel and surfaces of these same materials. Similarly, differences in static coefficients of friction also contributed toward the larger frictional forces between ceramic bracket-slots and uncoated archwires (CRC Handbook of Chemistry and Physics, 1986).

The significant bracket-archwire interaction noted means at least one combination of bracket and archwire generated frictional force such that the main-effect patterns were violated; the interaction is revealed by examining the table of means partitioned by bracket and archwire (Table 4-3). Coated archwires produced significantly less average friction than uncoated archwires in the polycrystalline bracket-slots. Although not statistically significant, a corresponding trend was observed from test results involving single-crystal brackets. Stainless-steel brackets, however, generated alike frictional forces when tested with the two archwires.

Deviation from the archwire main-effects pattern by specimens including stainless-steel brackets is likely a combined function of the surface roughnesses of the bracket-slots and the relative hardnesses of the contacting surfaces. As described, the surfaces of the polycrystalline bracket-slots were apparently rougher than surfaces of the other two brackets. In addition, ceramic brackets are harder than those of stainless steel (Bowen, 1988; Swartz, 1988), and the stainless steel surfaces of uncoated archwires are harder than the Teflon surfaces of coated wires (Teflon Mechanical Design Data, n.d.; CRC Handbook of Chemistry and Physics, 1986).

When the surface irregularities of the ceramic brackets (especially polycrystalline) began to "dig into" the stainless steel surfaces of the uncoated archwires, the relatively hard stainless steel did not "give" as readily as did the softer Teflon coating material. This hardness difference led to significantly higher maximum static forces for the uncoated archwires than the coated archwires when tested with polycrystalline brackets, and the parallel trend found with single-crystal brackets. When tested with stainless-steel brackets, however, the combined effects of a smoother bracket surface and lower hardness value resulted in no .gnificant difference between static frictional forces with the two archwires.

Evaluation of Mean Kinetic Frictional Forces

The analysis-of-variance summary with mean kinetic frictional force as the dependent variable (Table 4-5) yielded significant main-effect influences from bracket and ligature wires, but not archwire. No significant interactions among independent variables were indicated. Stainless steel and single-crystal ceramic brackets were associated with statistically alike and smaller average frictional forces than were the polycrystalline brackets (Table 4-6), and the average frictional force from specimens with coated ligature wires was less than from specimens with uncoated ligation.

The larger mean kinetic forces recorded during tests with polycrystalline brackets are likely due to the same influences suggested for the larger maximum static forces from the same specimens: the greater surface roughnesses of these brackets. Similarly, the significant ligature-wire influence is explained by differences in the coefficients of kinetic friction (Stannard et al., 1986).

The analysis of variance of kinetic frictional forces (Table 4-5) did not yield a significant main-effect influence from archwire or a significant bracket-archwire interaction, as found in the analysis of static frictional forces. These unlike outcomes appear to result from abrasion of the stainless-steel archwires by polycrystalline brackets: similar magnitude patterns to those described for maximum static frictional forces from these specimens were found from the kinetic force analysis *except* that there was no significant difference in mean kinetic frictional resistances between coated and uncoated archwires contacting polycrystalline brackets. Examination of the ceramic brackets tested with stainless steel archwires showed dark discoloration that was most prominent near mesial and distal extents of the bracket-slot facial surfaces. This discoloration was more distinct on polycrystalline than single-crystal brackets, and apparently was accumulated metal shavings from stainless steel archwires that had been abraded by the ceramic brackets. As the bracket displacement proceeded, the irregularities of these brackets were apparently "smoothed over" with the metal shavings, the friction between the brackets and archwires became progressively less, and the resultant average frictional forces from specimens with coated or uncoated archwires were not significantly different.

Frictional Forces From Tests at Five-Degrees Angulation

Evaluation of Maximum Static Frictional Forces

The analysis-of-variance summary with maximum static frictional force as the dependent variable (Table 4-8), indicated significant main-effect influences from bracket and archwire, but not ligation, and a significant bracket-archwire interaction. Maximum static frictional forces associated with polycrystalline brackets were significantly higher than those associated with statistically alike stainless-steel or single-crystal brackets. Maximum static frictional forces from specimens including coated archwires were significantly smaller than those with uncoated archwires. Ligation was not a significant main-effect influence; apparently the normal forces exerted on the archwire by diagonally-opposite bracket-slot edges were more influential than the normal forces between archwire and ligation, resulting in the relatively insignificant influence from the latter.

Table 4-10 reveals two bracket-archwire combinations that did not follow the patterns of main-effects variables: 1) when paired with uncoated archwires, frictional forces associated with single-crystal brackets were significantly greater than with stainless-steel brackets; 2) the difference in mean static frictional forces, coated versus uncoated archwires tested with stainless-steel brackets, was not significant. These two outcomes are discussed in the following paragraphs.

As noted, brackets composed of ceramic materials are significantly harder than those of stainless steel, and Teflon surfaces are much softer than those of stainless steel. Additionally, the ceramic brackets tested had bracket-slot edges that were relatively sharp, in contrast with the somewhat rounded edges of the stainless steel brackets. These factors were apparently more influential in determining the maximum static frictional forces than were the unlike coefficients of static friction.

Surfaces of uncoated archwires tested with ceramic brackets displayed evidence of gouging and scraping, apparently from contact with the bracket-slot edge.

Several of the coated archwires tested with ceramic brackets displayed gouges through the coating material to the stainless steel core, with the coating material pushed in the direction of bracket displacement (Fig. 5-1). The Teflon material apparently tore when the hard, sharp edge of a ceramic bracket-slot attempted to move relative to a coated archwire, and motion apparently occurred concurrent with this tearing. From examination of test specimens, it is impossible to determine when the tearing first occurred in relation to the plot pattern, and what the contact relationship was between the bracket-slot edge and the archwire during the tearing. It seems likely, however, that the bracket-slot edge contacted the coating material throughout the test, and never directly reached the stainless-steel core.

Although the indentations of the uncoated wires did not appear as severe as those observed on coated wires, the impact on friction seems to have been greater. When the ceramic bracket-slot edge attempted to move relative to an uncoated archwire, the stainless-steel surface of the uncoated archwire resisted bracket displacement more forcefully than the softer Teflon surface of the coated archwires. Ultimately, this resistance was reflected as greater frictional forces generated between ceramic brackets and uncoated archwires compared to coated archwires.

Fig. 5-1. Coated archwire segment displaying evidence of gouging through the coating material toward the stainless-steel core.

When tested with stainless steel brackets, the rounded slot edges (and, perhaps the stainless-steel material itself) did not cause significant gouging into the surfaces of either archwire. Coated archwires were somewhat "roughened," and small indentations were occasionally noted, but the uncoated archwires showed little or no evidence of wear. These observations explain the lack of significantly different maximum static frictional forces generated by the two archwires with stainless steel brackets that was exhibited with both ceramic brackets.

The above observations seem to adequately explain the significant bracket *and* archwire influences on maximum static frictional forces indicated by the analysis of variance; however, the potential for influences from different archwire bending stiffnesses should also be considered. Although the outer diameters of the two archwires were the same, the coated archwire segments were composites of a 0.012-inch-diameter stainless-steel core with 0.003-inch-thick Teflon coating. Because of the lower stiffness of Teflon compared to stainless steel (Teflon Mechanical Design Data, n.d.), the unit bending stiffness of the coated wire was less than that of the uncoated wire. The impact of archwire stiffness on friction during these tests was suppressed by "pre-tensioning" the archwire segments. Results, notably, do not indicate a strong influence of archwire stiffness in the present study.

Had the differences in effective bending stiffnesses of coated and uncoated archwires been significant, greater normal forces exerted by the stiffer uncoated wires on bracket-slot edges during tests conducted at five-degrees angulation would have generated greater average frictional forces, independent of the bracket. Although the uncoated archwires did produce higher frictional forces against the ceramic brackets, no such finding emerged from the subsamples involving stainless-steel brackets. Summarily, differences in bracket-slot and archwire surface hardnesses, surface roughnesses, and sharpness of the bracket-slot edge seem to explain the outcomes independent of differences in archwire stiffnesses, and were apparently more influential in determining maximum static frictional forces than differences in the coefficients of static friction alone.

Evaluation of Mean Kinetic Frictional Forces

The analysis-of-variance summary with mean kinetic frictional force as the dependent variable (Table 4-12) indicates significant main-effect influences from bracket and archwire, with a significant interaction between these two variables. No significant influence by ligation is indicated. Average frictional-force values from specimens including polycrystalline brackets were significantly greater than those obtained with stainless-steel or single-crystal brackets (Table

4-14). Coated archwires produced smaller mean kinetic frictional forces than uncoated archwires against polycrystalline ceramic brackets. A strong trend emerged toward smaller frictional forces with coated versus uncoated archwires against single-crystal ceramic brackets, but no difference was noted between kinetic frictional forces associated with coated archwires versus uncoated archwires and stainless-steel brackets.

Differences in bracket-slot and archwire surface hardnesses, surface roughnesses, and slot-edge finishing (sharp versus rounded) again seem to adequately explain the data. The sharp edges of the ceramic brackets digging into the stainless steel of the uncoated archwire surface impeded motion more than against the coated archwires, the difference being significant for the polycrystalline brackets. The rounded edges of the stainless-steel brackets produced no difference in frictional forces between the two archwires. The surface roughness of the polycrystalline bracket caused greater frictional forces than either of the other brackets in combination with either of the archwires.

When brackets from the five-degree tests were examined, the discoloration of ceramic brackets tested with uncoated archwires was heaviest near the mesial and distal extents of the facial slot surface and on the diagonally-opposite bracket-slot edges that contacted the stainless-steel surface (Fig. 5-2). Again, this observation reflects the surface abrasion of the uncoated archwire by the ceramic brackets.

Maximum Static Frictional Forces Compared to Mean Kinetic Frictional Forces

With the classic block-on-plane model, frictional forces generally decrease after the initiation of movement, and then remain relatively constant during motion (Beer and Johnston, 1984), a relationship that was not consistently observed during this experiment. Although the combined average for all tests conducted at zero-degrees angulation gave a mean maximum static frictional force slightly greater than the mean kinetic frictional force, tests conducted at five-degrees angulation yielded kinetic frictional forces that averaged over 20 grams *more* than the corresponding maximum static frictional force. These results are explained by evaluating the test fixture (Fig. 3-2) and the testing procedure.

The influence of wire stiffnesses on friction is well-established; for a given wire segment supported similarly at both ends, the cross-section of least resistance to lateral deflection is midway between the two supports, with increasing resistance to deflection as the load site is moved toward either end (Nikolai, 1985). In the present study, the initial position of the bracket was at approximately the midpoint of the archwire segment. As the bracket was displaced during testing, the local stiffness of the archwire segment increased. The greater stiffness had little (if any)

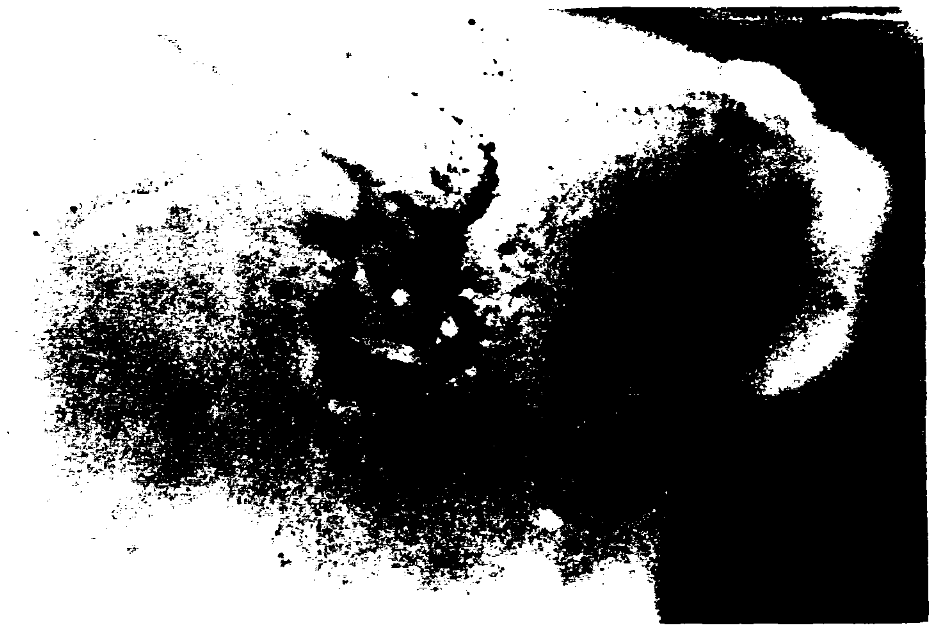

Fig. 5-2. Polycrystalline bracket from a test with an uncoated archwire at five-degrees angulation displaying evidence of discoloration from stainless-steel archwire abrasion.

effect on tests conducted at zero-degrees angulation because the normal forces in this situation are exerted primarily in a faciolingual direction. For tests at five-degrees angulation, however, the increased effective wire stiffness caused increased normal forces at diagonally-opposite slot edges and, therefore, increased resistance to bracket displacement (i.e., increased frictional forces) (Figs. 2-1A, 2-1C). The result of this sequence was a mean kinetic frictional force that was generally greater than the mean maximum static frictional force from tests at five-degrees angulation.

The effects of each independent variable (i.e., bracket, archwire, or ligation) on maximum static frictional forces seemed, from results of the present study, to generally parallel the effects of the same independent variable on mean kinetic frictional forces. This point is illustrated by comparing the respective tables of cell means (Tables 4-4 and 4-7; Tables 4-11 and 4-15). The patterns of relative force magnitudes among the various bracket/archwire/ligation combinations are nearly identical between comparable tables. These observation suggest that, within the scope of the present study, values for maximum static frictional forces might have been reasonably well predicted from the mean kinetic frictional-force outcomes.

The possibility was considered that the values for mean kinetic frictional forces, determined by first averaging ordinates of eight discrete points from the plot generated by each specimen, might be more accurate than the values for maximum static frictional forces, determined by a single point from each plot. The averaging procedure used to calculate the mean kinetic frictional force was more structured than the single-point estimation for the static friction, potentially signifying greater confidence in the former measurement. Results, however, did not support this supposition: 1) the mean-square error values (estimations of the portions of the force values that were not attributable to the independent variables) from the analyses of variance for the maximum static frictional forces at either angulation were not generally larger than the corresponding value for mean kinetic frictional forces; 2) as mentioned, similar force-magnitudes patterns, static versus kinetic friction, resulted at both angulations. This evidence suggests that the point of maximum static frictional force may be reasonably selected within a rather complex force-displacement plot.

Outcomes at Zero-Degrees Versus Five-Degrees Angulation

The normal contact forces at zero-degrees angulation arise from the ligation and are directed primarily in a faciolingual direction, but sizable normal forces were also exerted by the bracket-slot edges in an occlusogingival direction during tests at five-degrees angulation. Previous bracket-wire friction experimentation demonstrated that increased angulation generated greater normal forces (from greater wire flexure) between bracket-slot edges and engaged archwires, producing greater average frictional forces (Frank and Nikolai, 1980). Although statistical comparisons of data from the zero-degree and five-degrees subsamples in the present experiment was not undertaken, the cell-mean frictional-force values from tests at five-degrees angulation were generally greater than corresponding values from tests at zero-degrees angulation (Tables 4-4, 4-7, 4-11, 4-15).

Ligation exerted a significant influence on maximum static and mean kinetic frictional forces from tests at zero-degrees angulation; however, no such significant influence was found from the test results at five-degrees angulation. As noted, this difference is attributable to the significant influences of normal forces generated between diagonally-opposite bracket-slot edges and the archwires at five-degrees angulation that were prominent elsewhere but smaller during the tests at zero-degrees angulation.

Evaluation of Plot Patterns

Plots generated by the recorder connected to the testing machine were examined in the order of preparation after all 144 tests were completed. In addition to the quantitative values for maximum static frictional force and mean kinetic frictional force determined for each specimen, each plot was studied individually and in relation to other plots from various subsamples to discern general patterns or characteristics present.

Plot patterns differed primarily with archwire and angulation. Coated archwires produced plots in which the frequency of "peaks" was much greater than for uncoated archwires (e.g., Fig 4-1A versus 4-1C), resulting in a "finer" pattern. These peaks represented the repeated release after initiations of "friction-locks" between the ligated bracket and the archwire. The coated archwire allowed the bracket to move by a series of "steps" or "jumps" that were more frequent in occurrence than with the uncoated wires, probably relating to the previously-discussed tendency for the Teflon material to "give" when applied forces attempted to displace the bracket relative to the archwire.

Also noted was that test specimens including uncoated archwires and ceramic brackets tended to produce plots with a definite point of maximum static frictional force (Figs. 4-1C, 4-2C); the initial "friction-lock" release between the coated archwire and ceramic brackets was not as distinct (Fig. 4-1B, 4-2B). This trend was especially evident in tests conducted at five-degrees angulation, and is likely related to the tearing of the coating material by the bracket-slot edge. As the coating material was displaced by the bracket, the bracket moved slightly, and the concurrent movement of the recorder was interpreted as the maximum static frictional force. Examination of the archwire segments following testing, however, indicated that this initial movement for some specimens was likely due to tearing of the coating material, and not an actual break of the "friction-lock." The added resistance of this material was indicated by the immediate increase of force following the initial bracket movement and, as the test proceeded, resistance continued to increase as the coating material "bunched up" ahead of the moving bracket.

Differences in overall kinetic-frictional-force patterns were also observed among the various bracket-archwire combinations. Test specimens including stainless steel or single-crystal brackets tested at zero-degrees angulation produced kinetic frictional forces that remained relatively steady (Fig. 4-1A, 4-1B). Kinetic frictional forces associated with polycrystalline brackets tested with uncoated archwires at zero-degrees angulation, however, tended to decrease as bracket displacement proceeded (Fig. 4-1C), likely related to "smoothing" of the rough ceramic surface by abraded stainless-steel shavings from the uncoated archwires.

From tests at five-degrees angulation, specimens often produced plots that indicated kinetic frictional forces increasing with relative displacement. The general slope of the plot became significantly steeper toward the end of the bracket displacement (Fig. 4-2A, C). This phenomenon is a reflection of the greater archwire bending stiffness encountered as the bracket was displaced toward the testing apparatus end-support.

Comparisons with Previous Studies

Kusy (1988) studied the surface morphology of a polycrystalline bracket using scanning electron microscopy and found it to be "rough like a concrete block rather than smooth like its stainless steel counterpart." Kusy also referred to an unpublished study by himself and Whitley that compared frictional forces associated with polycrystalline ceramic brackets and stainless steel brackets. This study showed "...the coefficients of friction of one polycrystalline bracket...significantly greater than those of steel..." Results from the present investigation support the findings of both these studies. No report of similar research involving single-crystal ceramic brackets has apparently been published in the orthodontic literature.

Coefficients of static and kinetic friction reported for Teflon surfaces against stainless steel are smaller than equivalent values for stainless steel against itself (CRC Handbook of Chemistry and Physics, 1986; Stannard et al., 1986), and measured hardness values for Teflon are smaller than equivalent values for stainless steel (CRC Handbook of Chemistry and Physics, 1986; Teflon Mechanical Design Data, n.d.). Results from the present study indicated that combined differences in surface hardness, surface roughness, and sharpness of the bracket-slot edges explained differences in static and kinetic frictional forces measured during sliding edgewise orthodontic mechanics more adequately than differences in the coefficients of static and kinetic friction alone, determined from experiments using flat surfaces.

Although Teflon may be potentially desirable as a coating material for orthodontic archwires due to its lower coefficients of friction with bracket materials (i.e., stainless steel or ceramics), the tendency toward surface cracking and peeling has historically limited its use (Greenberg and Kusy, 1979; Whitley, 1989). Results from the present study indicated that, although smaller frictional forces were generated with Teflon-coated archwires contacting ceramic brackets than stainless-steel archwires against similar brackets, the Teflon coating material was undesirably distressed by bracket-slot edges. This failure creates some question as to the viability of Teflon as an archwire coating material at this time, particularly when tipping of cuspids during retraction is anticipated.

Several orthodontic friction studies (Garner et al., 1986; Stannard et al., 1986; Baker et al., 1987) have determined coefficients of kinetic friction of test specimens, compared these values, and drawn conclusions about the relative effects on clinical orthodontic friction from the relevant independent variables. According to Frank and Nikolai (1980), kinetic friction may not be as clinically relevant as maximum static friction when evaluating orthodontic forces because of the pattern of tooth movement in "steps" or "jumps" rather than as a continuous motion. The results from the present study showed that there did not seem to be significant effects exerted by brackets, archwires, or ligation on one of these measurements and not the other, and that, for the variables evaluated, the relative effects on maximum static frictional forces could be predicted from the outcomes of mean kinetic frictional forces.

Clinical Relevance of the Present Study

The awareness and management of frictional forces is an important consideration when planning orthodontic tooth movements (Proffit, 1986). The present study demonstrated differences attributable to appliance components in the maximum static and mean kinetic frictional forces during simulated sliding orthodontic edgewise mechanics. By comparing the average maximum static frictional forces generated by different bracket/archwire/ligation combinations given in the tables of cell means (Tables 4-4, 4-7, 4-11, and 4-15), the orthodontist can predict the relative frictional forces to be generated within a given appliance. This information should be useful in selection of appliance components in a given clinical situation. If intraoral sliding mechanics are anticipated by the orthodontist in an instance that requires maximum "anchorage" preservation, for example, single-crystal brackets and coated archwires would seem to be as satisfactory a selection as stainless-steel components to satisfy both the esthetic and friction concerns of patient and practitioner. Polycrystalline brackets with uncoated archwires would not be desirable in this situation, as the relatively large applied force required to initiate displacement of a tooth with bracket affixed would generate responsive forces acting on the posterior "anchorage" teeth that could potentially cause undesirable movement of these teeth anteriorly.

Suggestions for Future Research

Several areas of investigation related to the present study or arising as a result of information gained from this research remain:

1) The determination of maximum static and mean kinetic frictional forces between slots of stainless-steel, single-crystal ceramic, and polycrystalline ceramic brackets and archwires of various metal alloy compositions, sizes and shapes (including rectangular wires, in particular).
2) The determination of frictional forces between cited archwires and bracket-slots, the ligation by means of elastomeric modules and eliminating the pre-tensioning of the

archwire segments.

3) The determination of frictional forces associated with ceramic attachments that have more rounded bracket-slot edges, and comparison of these frictional forces with those obtained in stainless-steel brackets slots.

The clinician must consider several factors in addition to the influences on frictional forces when selecting the individual brackets, archwires, and ligation to compose an orthodontic appliance. The structural properties of the appliances (e.g., wire stiffnesses, bracket fracture strengths, etc.), the anticipated mechanics of tooth movements, cost of the appliance components, desires of the patient for an esthetic appliance, and the familiarity of the orthodontist with the components are all important. Although the ceramic brackets and coated archwires are esthetically appealing to many patients and clinicians, the structural limitations of these appliance components compared to those of stainless steel (i.e., increased friction from polycrystalline ceramic brackets; reduced bonding stiffnesses compared to homogenous, traditional wires and surface distressing of the coated archwires) must also be considered.

The present study provided information about the frictional forces encountered during orthodontic tooth movement using stainless steel, polycrystalline ceramic, and single-crystal ceramic brackets; archwires of uncoated and Teflon-coated stainless steel; and ligations of uncoated and Teflon-coated stainless-steel wires. This information may prove beneficial in helping the clinician select the appropriate orthodontic appliance.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

This investigation sought to measure and compare the frictional forces generated within a relevant sample of test specimens during simulated orthodontic sliding mechanics. Each specimen consisted of an orthodontic bracket, an archwire segment, and ligation. Brackets were of stainless steel, polycrystalline aluminum-oxide ceramic, or single-crystal aluminum-oxide ceramic; archwires and ligature wires were solid stainless steel or a stainless-steel core coated with Teflon.

To isolate the effects of material surfaces on friction, other parameters generally considered to influence friction in a bracket-wire system were controlled constants. These parameters included length of the archwire segments, archwire and ligature-wire diameters, occlusogingival and mesiodistal bracket-slot dimensions, interbracket distances, and ligation design and force. Simulation of an intraoral environment was created via immersion of test specimens in a saliva-substitute medium. Additionally, the influence of archwire stiffnesses on friction was suppressed by "pre-tensioning" the archwire segment prior to each test.

Dependent variables quantified were the maximum static frictional force (the force required to initiate movement of the bracket relative to the archwire) and the mean kinetic frictional force (the average force generated during a 1.1 millimeter movement of the bracket along the archwire segment). A total of 144 bracket-archwire-ligation specimens were tested: six repetitions of each combination of independent-variable values in a 3 X 2 X 2 random-block format (three bracket values, two archwire values, and two ligature-wire values) within each of two primary subsamples defined by zero and five degrees of relative bracket-slot/archwire angulation.

Plots of frictional force versus relative displacement generated by a recorder connected to the testing machine were examined in the sequence prepared after all 144 tests were completed. In addition to the quantitative values recorded for maximum static frictional force and mean kinetic frictional force, each plot was studied individually and in relation to plots from various other subsamples (i.e., other combinations of independent-variable values) to discern general patterns and pertinent characteristics present.

Analyses of variance of maximum static frictional force and mean kinetic frictional force were performed for each of the two primary subsamples. Tukey's Honestly Significant Difference post-hoc test was carried out as necessary to determine statistically significant differences between group means.

Statistical analyses of the specimen data and examinations of the test specimens themselves led to the following results:

1. Stainless-steel and single-crystal ceramic brackets were generally associated with statistically alike maximum static and mean kinetic frictional forces at both angulations. Corresponding forces associated with polycrystalline brackets were generally greater.

2. A trend emerged toward smaller static and kinetic frictional forces associated with the coated archwire than with the uncoated archwire when interacting with either ceramic bracket. This trend was especially evident within the subsample defined by five-degrees angulation. Subsamples with stainless-steel brackets showed no significant archwire influence at either angulation.

3. From the tests conducted at zero-degrees angulation, the maximum static and mean kinetic frictional forces were significantly smaller in the presence of coated ligature wires versus uncoated ligature wires. No significant influence of ligation on either

frictional-force value emerged, however, from tests at five-degrees angulation.

4. Examination of test specimens revealed greater surface distressing of archwires tested with ceramic brackets than those engaged in slots of stainless steel brackets. The uncoated archwires tested with ceramic brackets exhibited more severe gouging and scraping of the stainless steel surface than did alike wires engaging stainless steel brackets, and some coated archwires tested with ceramic brackets displayed gouges through the coating material to the stainless-steel core. Ceramic brackets engaging uncoated archwires were "discolored" by stainless steel that had been abraded from the wire surfaces. Polycrystalline brackets showed greater discoloration than the single-crystal brackets.

5. Coated archwires produced force-displacement plots with a greater frequency of "peaks" (representing the repeated releases after initiation of "friction-locks" between the ligated bracket and the archwire) than uncoated archwires.

6. Maximum static frictional forces and mean kinetic frictional forces were generally affected in parallel manners by the indepen-

dent variables; i.e., there did not seem to be significant effects exerted by bracket, archwire, or ligation on one of the frictional forces and not the other.

With respect to these summarized results, the following conclusions were drawn:

1. Because of their greater relative surface roughnesses compared to stainless-steel or single-crystal ceramic brackets, polycrystalline brackets tend to be associated with larger maximum static and mean kinetic frictional forces.

2. Because of their greater hardnesses and sharper bracket-slot edges compared to those of the stainless-steel brackets, the ceramic brackets selected for this investigation will cause greater distressing of all archwire surfaces during sliding mechanics.

3. Existing Teflon-coated archwires may be unsuited for sliding orthodontic edgewise mechanics (i.e., cuspid retraction) because of the tendency toward distressing of the soft outer surface compared to conventional stainless-steel archwires.

4. Future related research should focus on quantification and comparisons of orthodontic

frictional forces generated by stainless-steel, polycrystalline, or single-crystal ceramic brackets with ligated archwires of different sizes and shapes (rectangular archwires in particular), with elastomeric-module ligation, with elimination of the "pre-tensioning" of the archwire segment, and involving ceramic brackets with rounded bracket-slot edges.

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Dr. Gill was commissioned as an officer in the United States Air Force in July, 1982, and has since served for seven years. This service has included the completion of a dental general practice residency at Travis AFB, California, in 1983 and a three-year tour of duty in West Germany. In 1987 he began graduate studies in the Department of Orthodontics at St. Louis University, St. Louis, Missouri, where he is currently a candidate for the degree of Master of Science in Dentistry.

Dr. Gill and his wife, [redacted] The family will be returning to West Germany in July, 1989, where Major Gill will serve as an orthodontist at the Wiesbaden Regional Medical Center.