FRICTION AND BINDING
IN ORTHODONTIC APPLIANCES

by

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I N T R O D U C T I O N

Friction plays a very important part in nearly all everyday activities. Without friction, nails, screws, and moving belts would be useless; trains and automobiles could not start, but if going could not stop without a mishap; and one's ability to walk would be lost.[1] Friction also has detrimental effects on certain activities. It can produce excessive heat, wear, or even destruction of machines and materials. It acts to alter the efficiency of any mechanical device including orthodontic appliances.

Orthodontic appliances apply forces to teeth and the teeth respond by moving through the supporting bone. The magnitude of force which most efficiently moves teeth is not well known. In 1932, Schwartz[2] reported the results of his investigation of applied force related to tooth movement using a histologic approach. He concluded that a force which does not exceed capillary blood pressure (20-26 grams per square centimeter) is most favorable for tooth movement (an average permanent bicuspid tooth contains roughly one square centimeter of root surface.)

Storey and Smith[3] (1952) reported that a force of 200 to 300 grams per tooth causes the most efficient movement. They concluded that forces above or below this level would not move teeth as well and that a cessation of movement could result if high forces were used.

To more fully understand the nature of the biologic response of the supporting structures of a tooth to applied forces, a series of studies have been undertaken to determine the rate of tooth movement at various force applications at the University of Oregon Dental School.[4,5] These studies showed a wide variation in individual response to force application and showed that in general, higher forces tended to produce the most tooth movement.

In order to gain meaningful information on the rate of response of a tooth equated with various forces per unit area of root surface, it is desirable to produce bodily tooth movement. It becomes difficult to examine any theory of rate of tooth movement when tipping movements of teeth are obtained. Tipping produces a gradient of force values along the supporting alveolor bone. Bodily tooth movement gives a more nearly equal distribution of force to the bone along the tooth roots, although the force per unit area still cannot be considered equal along the entire root area owing to the curved contours of tooth roots.

Bodily tooth movement was obtained in only about one half of the teeth tested in the two earlier investigations at this institution.[4,5] A new study was initiated to further evaluate force to tooth movement and anchorage using an appliance constructed of rigid materials in hopes bodily movement would be found in a higher percentage of cases. The nature of this appliance introduces problems of accurate force determination because of the friction factor.

This paper will be concerned with:

1. a description of the appliance used,
2. an evaluation of the maxiumum tipping allowable,
3. an evaluation of the frictional resistance in the appliance and,
4. an evaluation of the effect of friction in the edgewise appliance.

REVIEW OF THE LITERATURE

Frictional force is defined as that force acting parallel to two surfaces which is necessary to overcome the resistance between these surfaces when a force is acting perpendicular or normal to these surfaces. The coefficient of friction (u) is the ratio of the frictional force to the normal force.

$$U = \frac{F = \text{frictional force}}{N = \text{normal force.}}$$

The coefficient of friction for two unlubricated metal surfaces in contact generally ranges from 0.15 to 0.25.[6]

Static friction exists when there is no movement between two surfaces and it is the amount of force needed to just initiate movement. Kinetic friction (sliding friction) exists when there is relative movement between two surfaces. Kinetic friction is generally slightly less than static friction.[7]

Leonardo do Vinci[8] (1482-1519) was the first to develop basic concepts of friction. Some of his conclusions were:

1) frictional resistance is proportional to roughness,
2) frictional resistance is doubled when the load is doubled,
3) a body resists movement down an incline plane with 1/4 of its weight.

Palmer[1], in his historical review of friction, cites the important contributions of Amontons and Charles Couloumb to our understanding of friction. Amontons (1663-1705) was a French physicist who first described the mathematical relationship of dry friction in solid bodies. He concluded that frictional resistance:

1) is proportional to the force (load) of one material resting upon another,
2) is independent of the area of contact between the two surfaces.

These two conclusions have traditionally been considered the first two so-called "classical" laws of friction. The coefficient of friction was described mathematically by Amontons as F=Un (Amontons Law).

Couloumb in 1785 added to the classical laws by stating:

1) frictional force is independent of velocity,
2) friction depends upon the nature of the materials in contact (surface roughness).

He theorized that friction was due to the intermeshing of microscopic asperities, much as the bristles of two hair brushes engage when rubbed together.

Modern day thought has tended to replace some of the "classic" laws of friction. Palmer[1] has restated the first three laws exactly opposite from their original wording:

1) frictional force is independent of load,
2) frictional force is directly proportional to the area of actual contact,
3) frictional force depends upon the velocity of sliding and in the higher range decreases with increasing velocity,
4) frictional force depends upon the nature of the materials in contact.

Palmer reasoned that friction was independent of roughness, in that the results of 100 friction measurements on each of five different metals were essentially the same whether the surfaces were polished, or rough and torn. The friction of groundglass was found to be less than that of polished glass. The coefficient of friction is usually the same for a material slid over a freshly prepared surface as though the same visible groove of an original trip.

Palmer differentiates actual area of contact between two surfaces from apparent area of contact. When two surfaces are placed together, microscopic projections come into contact. Increasing the load on these surfaces causes elastic deformation of these projections thus bringing more material into contact. This increases the actual area of contact without changing the apparent area of contact.

Palmer[1] mentions the phenomenon of "stick-slip" which occurs when some materials are moved slowly over other materials. The movement proceeds in small jerks, their magnitude depending upon the velocity of force application. This happens, for example, when a violin bow is moved across the strings, and is responsible for sound production in the violin.

Wild and Beezhold[9] state that static friction is variable and determined by the rate of application of forces. As velocity increases, the coefficient of friction is decreased for kinetic friction and increased for static friction. At very low speeds, and absolutely clean surfaces, static friction is equal to kinetic friction.

Bowden and Taber[10] found that the first "classical" law that friction is proportional to load generally holds except for special conditions such as the presence of dissimilar metals or oxides between the sliding surfaces. They also describe the mechanism of friction as due to the shearing of intermeshing surface irregularities and thus equate the coefficient of friction with a ratio of shear strength to hardness. Another theory described by Tomlinson[11] explaining the mechanism of friction, holds that forces of molecular attraction cause adehesion and cohesion thus providing frictional resistance. The actual mechanism of friction is probably due to a combination of several factors.

Rabinowicz[12] cited the large influence of temperature, humidity, cleanliness, and atmospheric composition on the coefficient of friction. Frictional force values measured in a vacuum are much different than those obtained in the atmosphere. The formation of oxides on metals acts similar to a lubricant to reduce friction. Rabinowicz advanced a theory for action of a lubricant which proposes that lubricants act to reduce the forces of adhesion between two surfaces, thus reducing the frictional forces.

A theory for the mechanism of action of lubricants is advanced by Mitinsky[13]. He states that the lubricant fills the hollows in the sliding surfaces between the micro-projections and the shearing off of these projections is reduced. Also the lubricant increases the number of actual contacts thus decreasing the amount of the load on any one contact, hence the friction is less.

Palmer[1], in his discussion of lubrication, cites the importance of the viscosity of the lubrication in determining the amount of friction reduction that it produces. A lubricant contains a certain amount of inherent friction, dependent upon its viscosity. Highly viscous lubricants have more value in reducing friction when heavy loads are used, in that the lubricant is not displaced out from the opposing surface areas. When the load is small, a thin film lubricant with less inherent friction can be used.

The mechanical journals show a wide divergence of opinion on the nature of friction. In the orthodontic literature, "friction" exists between individuals but discussions of friction between brackets and wire are few and far between. Neither Case[14] nor Angle[15] mentions friction in the early orthodontic literature.

Possible explainations of why friction was not considered are:

1) the philosophy of non-extraction necessitated less sliding of brackets on wire and therefore less total friction,
2) the appliance moved teeth, so there was no need to consider friction.

With the change in philosophy toward more extraction treatment, a few discussions of friction are included in the literature. Most of these discussions are based on opinion, however, and very few articles utilize scientific methods for evaluating the friction in an orthodontic appliance.

Multiple loop arch wires and closing loops bent into arch wires have been used with the idea of reducing the effect of friction of wires in brackets. Stoner[16] states that applied forces in orthodontic appliances can be dissipated by friction. He describes many different types of multiple loop arches which do not require the sliding of wires through brackets. This would remove friction as a factor in reducing appliance efficiency.

Begg[17], in describing his techinque, states that friction must be minimized in the buccal segments when tipping back the anterior teeth. This he accomplishes by using small wires relative to tube and bracket size. He also says that the arch wire must extend completely through the buccal tubes of the molars to prevent the end of the wire from binding within the tube.

Burstone[18] describes his segmented arch technique as a "frictionless mechanism of cuspid retraction". He feels that sliding a tooth along an arch wire creates a considerable amount of friction, since the center of resistance of the root of the tooth is far from the crown.

Two general schools of thought exist concerning the mechanism of friction between a wire and a bracket. These views hold that:

1) friction is dependent upon the amount of freedom between the arch wire and bracket and can be overcome by increasing the force,

2) friction is dependent upon binding at the edges of the bracket and is increased by the increasing the force.

These two theories state opposing views in that a small arch wire with more bracket clearance would tend to produce more binding through the indenting of the wire by the bracket edges.

Stoner[19] (in Graber's book) follows the first view and emphasizes the necessity for loose ligature ties to prevent binding, subdued offsets in arch wires, and smaller wire sizes in relation to bracket size. He states that if anchorage units have a good resistance capacity, forces of greater intensity can produce successful tooth movement, even in the presence of friction.

Andreasen[20] mentions friction as a detrimental factor as wire size approaches bracket size. Paulson and Isaacson[21] refer to friction as one of the important variables in their study of cuspid retraction. They consider tight ligatures a factor in increasing friction and use an .016 wire in an .018 bracket to allow clearance for sliding.

Thurow[22] takes the second view on the mechanism of friction. To him, the two factors which determine friction are the coefficient of friction and the total force between the surfaces. Apparent area of contact is not a factor because increasing the area of contact adds friction creating surfaces at exactly the same rate as it reduces force per unit area so that these effects neutralize each other. He feels that the area of contact is important only in the case where at least one surface becomes so small that it deforms the opposing surface, such as a sharp bracket edge indenting an arch wire. He concludes that the important variable in friction is bracket width. A wide bracket would give less binding at the bracket edges and thus less friction. Thurow also states that increasing the forces in the appliance will only increase frictional force.

Ringenberg[23] follows the same reasoning as Thurow and favors wide twin brackets over single brackets to prevent tipping and thus binding at bracket edges. He dislikes retracting cuspids along an arch wire and prefers vertical loops for retraction to reduce friction.

Jarabak[6] states that the greater the pressure component against the inside of the bracket or tube, the greater the force necessary to make the wire slide. His light wire technique utilizing multiple loops and small diameter wires, though based on his belief in the optimal force theory[5], seems also to be founded on his rational for reducing frictional forces. His view is that as a tooth tips it becomes bound by friction and binding, then it uprights slightly as bone is resorbed and the binding is reduced so that it can slide along the arch wire again. Jarabak states: "force magitude, friction, and appliance ridgidity are important in the over-all consideration of root resorption during orthodontic treatment."

Of the few experimental attempts mentioned in the literature to measure friction in orthodontic appliances, all have been in vitro tests. Nicolls[24] tested frictional forces in edgewise appliances by pulling wires through brackets with forces acting at various angles. He found:

1) higher angles of wire to bracket gave higher friction values,
2) narrow brackets allowed more tipping and binding thus more friction,
3) tight ligatures gave more friction which decreased as the wire slid and the ligature became loosened,
4) more resilient wire gave less friction,
5) bending loops in wires reduced friction,
6) elastics pulling against an arch wire added frictional resistance.

Andreasen and Quevedo[25], obtained findings similar to Nicolls, in an in vitro test of friction in edgewise appliances. They also found that the frictional forces of wires through brackets with saliva as a lubricant were not significantly different from a dry wire in a bracket. Their findings show friction to increase in a geometric rate as the wire size approximates the bracket size.

One of the few references to jiggling forces of mastication and muscle action moving the arch wire and tooth slightly to help overcome friction is from Jarabak[6]. This theory of overcoming friction through vibration is also described by S.S. Miller[26] and Hixon, et al[5]. Miller used a mechanical vibrator to simulate this jiggling in an in vitro test of an appliance designed to evaluate the rate of bodily tooth movement. His conclusions were that static friction increased in a linear proportion to increase in forces, while vibrating friction remained at a constant value of approximately 5% of the applied force throughout a force range from 50 to 1400 grams.

Devising an in vitro experiment to evaluate friction in orthodontic appliances must include a discussion of the center of resistance. The center of resistance is defined as that vector of force into which all forces of a moving tooth root against the supporting periodontium may be resolved.

Burstone[27] states that the center of resistance of a tooth moving in pure translation is located at a point 40% of the distance from the aleolar crest to the apex and coincides with the geometric centroid of the tooth. For tipping tooth movements the center of resistance can vary from a point near the alveolar crest of bone to the centroid, depending on the amount of force applied and shape of the root. When a couple is placed on a tooth the center of resistance can vary between a point apical to the alveolar crest to a point near the root apex, depending on the magnitude of the couple. When the value of a couple is high, such as in bending a wire to produce heavy torquing forces to anterior teeth (lingual root torque), the center of resistance may approach the root apex.

The center of resistance of a tooth must be differentiated from the center of rotation, which is that point about which a tooth rotates when moving. A difference of opinion exists as to the location of the center of rotation and factors which influence its location.

The center of rotation has been described by various investiagtors as:

1) located a little apical to the center of the root,[2]

2) located at the apex of the root,[28].

3) located at the alveolar margin, (Bauer and Long quoted in Openheim[28]),

4) varying with force magnitude,[29].

5) varying with the location of force application.[2]

Christiansen and Burstone[30] refer to a formula for computing the theoretical axis of rotation based on a moment to force ratio. The predicted values of the center of rotation with this formula were within ± 3 mm. of the actual experimentally determined centers of rotation.

S.I. Miller[31] found that tipping forces applied to teeth produced instantaneous rotation around points varying from the alveolar crest of bone for lighter forces to positions near the junction of the cervial and middle root thirds at heavier loads. Rotational axes from longer term tipping force applications were located apical to the root. He postulated that elastic deformation of bone was a factor in influencing bone deformation.

Grimm[32] studied elastic deformation of interseptal bone in humans and found that the application of force to a tooth produced an initial small but measurable deformation of bone in a direction opposite to the direction of force application. His findings indicate that varying axes of rotation exist with different types of force applications, tipping or couple.

MATERIALS AND METHODS

Discription of Appliance:

An appliance was constructed which was hoped would produce bodily movement of mandibular cuspids, mandibular bicuspids and mandibular molars. Nine patients, 6 female, 3 male, ages 12 to 15 years, all caucasian, were selected. A criteria for selection was that they have minimal lower anterior crowding so that loss of molar anchorage would not necessitate early termination of the experiment, and the severity of their malocclusions had to be such that four first bicuspids needed to be extracted to complete their orthodontic treatment. Appliances were not placed in the upper arch because the need to use head gear against maxillary molars adds variables which can not be properly equated in different patients.

After removal of the first bicuspids, the mandibular cuspids, second bicuspids and molars were banded, impressions were taken, the bands were seated in the impressions and poured in plaster. Round tubes with an inside diameter of .045 and an overall length of approximately 20mm. were soldiered parrallel to each other on the buccal and lingual surfaces of the molars and bicuspids. These were stabilized by a holding jug during soldering to insure their parallelism.

An .045 highly polished stainless steel wire was then extended through each tube, held parallel with plaster and soldered to the cuspids. Hooks were then soldered on the buccal and lingual to the .045 wire in the cuspid area and to the .045 tubes in the bicuspid region so that springs could be attached which would apply a distal force on the cuspids and a mesial force on the bicuspids and molars (Fig.1, appendix).

The springs (Unitek Pace Multicoil, heavy, medium and light) were calibrated on an Instron tensile testing machine so that they would deliver a certain force at a predetermined length. The hooks in the bicuspid area were constructed so that shims could be added which would increase the length of the springs and maintain their desired force level as the teeth moved. By applying equal forces on the buccal and lingual of the teeth and sliding the teeth along relatively ridgid rails, it was felt that variables introduced by rotations would be substantially reduced.

Tubes (.022) approximately 3mm. long were soldered vertically to the buccal of the cuspid and molar bands. These vertical tubes were used to hold .022 stainless steel posts 10 mm. in length when taking radiographs, so that points of reference would be available for evaluating tipping and measuring tooth movement (see Cruikshank[33] and Nixon[34]).

An appliance was cemented in each of the two lower quadrants of the nine patients with zinc oxyphosphate cement (Fig. 2, appendix). The patients were seen at one week intervals, impressions were taken over the appliances at that time, and the springs were measured and adjusted as need to deliver the proper predetermined force. Force values of 100, 300, 500, 700, and 1000 grams were assigned randomly to each patient and the same force was applied to the two appliances in each patient.

Testing of Appliances:

To evaluate the friction in the appliance and the maximum tipping which it would allow, an apparatus was constructed which was believed would closely approximate the action of an activated appliance in the mouth. This apparatus consisted of a board with pulleys and a "C" clamp in which the actual appliances could be positioned and tested for deflection and friction (Fig. 3, appendix). Plaster was placed in the molar and bicuspid bands to prevent appliance deformation and the "C" clamp was tightened over the plaster. An .072 wire was fastened in the cuspid band with plaster to simulate the tooth root. A fine thread was fastened to the hooks on the cuspid, extended over one pulley and attached to a weight. Another thread was attached to the .072 wire at a point which would equal the apex of a mandibular cuspid. (Average values for teeth lengths were obtained from Greene Vardiman Black's measurements of teeth[35]). This second thread extended over another pulley to another weight of equal value. The first thread and weight provided the retracting force on the cuspid while the second thread and weight simulated the resistance of the alveolor bone to movement.

The apex of the tooth was chosen as the center of resistance in this test of deflection and friction because forces at this point would produce the maximum force couple between the wire and tube, thereby producing the maximum friction and wire deflection. The actual center of resistance is probably located near the centroid of a tooth, however, controversy over the location of this point, large individual variations in the shape and length of teeth, plus varying force applications make it difficult to select a valid point for force application. In choosing the root apex to apply resistance force, it is felt that a more reliable (reproducible) determination of friction and deflection is obtained. It is emphasized that the values of friction and deflection obtained in this investigation are the maximum that could be expected in the appliance and that actual values could be expected to be somewhat less with a shorter moment arm.

Two appliances were tested for maximum deflection by positioning them on the apparatus and applying force values ranging from 63 to 1032 grams. A traveling microscope was used to measure wire deflection from its resting position. This instrument could detect differences as small as 2.5 microns. The standard error of the measure was calculated to be .012 mm. Deflection was first measured for the .045 wire at the center of the cuspid crown over the solder joint with the cuspid band at a point 9 mm. from the mesial of the .045 tube. This would correspond with the average space available (7 mm.) for cuspid retraction and forward molar and bicuspid movement when a first bicuspid is extracted. The .045 wire was firmly fixed to the tube to prevent sliding during deflection measurements. Deflection was then measured at the root apex, and deflection in .072 wire (root simulator) was determined. By reducing the measured total deflection by the amount contributed by the .072 wire, total deflection of the root was determined. This deflection was then broken down into the amount contributed by deflection of the .045 wire and by deformation of the cuspid band.

Friction was measured in 10 of the 18 appliances by placing the appliances on the apparatus in the same manner as described for the deflection measurements, using equal weights in each direction. In this configuration, a state of equilibrium exists with a force couple present between the tubes and wires. If no friction at all existed, the reduction of the weight on one side by a minute amount would result in movement in the tubes toward the opposite direction. In this experiment, the weight on one side was progressively reduced until movement was just initiated. The amount of weight reduction necessary to start movement was considered to be the frictional force in the appliance.

To reduce the weight by a known amount an amalgam plugger equipped with two strain gauges (dynamometer[31]) was used to apply a force at the apex of the root opposite to the weight application at that point (Fig. 3, appendix). The strain gauges were connected through a Wheatstone Bridge circuit to a Sanborn strain gauge amplifier and graphic recorder. This instrument was calibrated before and after each appliance was tested, by hanging weights of known values from the amalgam plugger (Fig. 4, appendix). Weights as small as 2 grams could be determined with this device. Forces applied to reduce the weight of one side of the friction testing apparatus were registered on graph paper. That point at which the appliance started to slide was determined on the graph recordings (Fig. 5, appendix) as the point where the tracing leveled off and the friction value could be read directly from the graph. A similar method of measuring friction which used a device containing strain gauges to slide a sample of material along a surface at a constant rate with a lathe was reported by Sponseller and Gavan[36].

Since hand pressure was used to apply the dynamometer, slightly irregular graph patterns were obtained. To determine if differences in friction at different load applications were real, a range of frictional force values was read from the graph, and the mean friction value was computed. If no overlap in ranges was present, it was assumed that the differences were real.

An attempt was made to simulate the mechanical action of "jiggling" which occurs in the mouth through the action of mastication and muscle forces on orthodontic appliances. This was done by fixing an electric (60 cycle) vibrator to the back of the friction testing apparatus (Fig.6, appendix). This could then be turned on at a constant rate to test vibrating friction following each determination of static friction.

Approximately eight friction determinations were made on each of 10 appliances at 6 force loads

(63 to 1032 grams) under static and vibratory conditions. The mean of the friction values obtained was determined and a coefficient of friction was computed for each force application under static and vibrating conditions. This was not expected to be the true coeficient of friction between two stainless steel surfaces because of the presence of the couple between the wires and tubes. Using the term coefficient of friction provided a convenient means of expressing the friction to force ratio.

In order to determine the effect of saliva and lubricants on friction the following determinations were made. Two of these appliances (No. II and VII) were thoroughly cleaned with a brush, soap and water (cotton string was used to clean the inside of the tubes). They were dried and again tested on the apparatus for friction. Next they were soaked in saliva for 15 minutes and tested. They were kept saturated by intermittent applications of saliva with a camel's hair brush. These appliances were again throughly cleaned and tested for friction after lubrication. One (No. II) was well lubricated with a heavy grease (KEL-F Grease), and the other (No. VII) with a thin machine oil (Ritter Engine Oil).

Friction in the Edgewise Appliance:

Following the testing of the experimental appliance, the friction testing apparatus was modified slightly by the addition of a second "C" clamp at a distance of 20 mm. from the first clamp. These clamps could securely hold a strand of wire 20 mm. long, the approximate distance from the mesial of a bracket on a second bicuspid to the distal of a lateral incisor bracket. This situation would then be somewhat analogous to that existing when a cuspid is being retracted distally.

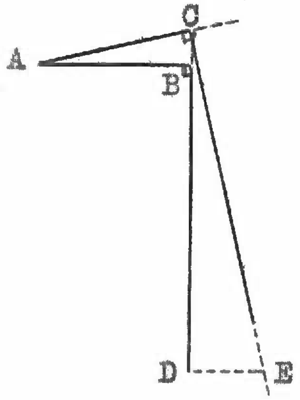
An extracted cuspid was banded and ligated to the secured wire. A load could then be placed on the tooth in a manner similar to that described in the friction test on the experimental appliance, and friction could be evaluated (Fig. 7, appendix). The load placed at the apex of the tooth was applied at a point slightly lingual to the apex, so that a maximum rotation component would be produced, thereby producing maximum friction.

A combination of twenty different conditions were set up on the apparatus and tested for static and vibratory friction at the six force loads used previously. These conditions consisted of using different wire sizes, (round and edgewise), various bracket widths,(siamese, Lewis brackets, and single brackets), different ligature ties, (tight, loose, heavy, light, and A-lastKs), and the influence of saliva.

FINDINGS

The mean deflection of the .045 wire at the cuspid band in an occlusal direction was found to range from .075mm. at 63 grams of force to .679 mm. at 1032 grams (Table I; Graph 1, appendix). The standard deviation from the mean was .043. The mean deflection at the root apex (after adjustment by subtracting the deflection in the .072 wire root simulator) was found to range from .159 mm. at 63 grams load to 2.287 mm. for 1032 grams (S.D. = .056).

A mathematical model was used to compute the amount of deflection at the root apex due only to bending of the .045 wire. (The values obtained should equal the measured deflection at the root apex if no bending of the cuspid band occurs).



In the above figure, if BC is the measured deflection of the .045 wire, AB = 9 mm. and BD = 19 mm., then the expected deflection at the apex $DE = \frac{(CB)\ (BD)}{AB}$.

The computed values for root apex deflection ranged from .158 mm. at 63 grams force to 1.433 mm. at 1032 grams. When compared with the measured values of deflection at the apex it was found that the measured values exceeded the computed values by a range of .001 mm. at 63 grams load to .854 mm. at 1032 grams. The increased values for measured deflection were believed due to a bending of the band material at higher force loads.

Four of the ten experimental appliances tested for friction were found to contain binding due to slight permanent bending of the wires. These appliances were not considered in the evaluation of tooth movement (Martins[37] and Nanson[38]) or of friction.

The mean friction values for six appliances varied from 26 grams to 350 grams over the force range for static friction and from 12 to 306 grams for vibrating friction (Table II, Graph 2). The coefficients of friction tended to be nearly linear throughout the force ranges with somewhat higher values obtained at the low and high ends of the spectrum (Graph 3). The range was from .266 to .405 for static friction and from .184 to .296 for vibrating friction. Vibrating reduced friction by an average of 27 grams with slightly higher reductions at high force values.

Friction values determined for the two appliances saturated with saliva were found to be higher than those with the same appliances tested dry. The static friction values over the forces tested ranged from 20 to 308 grams for dry appliances and from 54 to 504 grams with saliva (Table III, Graph 4). With vibrating conditions, a similar difference was found.

The effect of a heavy grease applied to one appliance was to increase the forces of friction slightly throughout the force range. A thin oil, applied to another appliance, increased friction slightly at the lower force ranges and decreased friction with higher forces (Table IV).

Tests on the edgewise appliance revealed fewer discernible differences in friction values than with those obtained on the experimental appliance. Some of the more apparent findings are listed below.

1) Tight ligature wires increased friction markedly, especially at the lower forces. After the wire slid through the bracket a small amount, the ligature would tend to become loosened and friction was reduced. Tight ligatures seemed to increase friction more in round wires than in rectangular wires due to the increased rotation and tipping allowed

by the round wires, producing more binding.

2) Alastiks increased friction at lower forces, and allowed bracket disengagement at higher loads.

3) Vibration caused less friction reduction in the edgewise appliance than in the experimental appliance.

4) The higher force loads on small wire sizes produced a binding of the brackets which markedly decreased sliding.

5) At light forces the friction for an .022 wire was very nearly the same as that for an .016 wire.

6) No significant difference could be detected when the bracket and arch wire were saturated with saliva.

7) Slightly lower friction values at low forces were obtained with the Lewis bracket, however, the variability was high.

8) No difference in the friction values for single brackets from twin brackets was observed at low force levels. At high forces, more friction existed with single brackets, due to binding.

9) No significant difference could be detected in the amount of friction in the .021X.025 edgewise wire from the .019X.025 wire.

DISCUSSION

The amount of deflection measured in the experimental tooth moving appliance shows the difficulty which exists in obtaining pure bodily tooth movement. The amount of tipping in the mouth would probably not approach the calculated deflection, due to the previously acknowledged overestimation of the moment arm to center of resistance, still tipping must be expected when heavy forces are used. A consideration of the deflection allowed by the band material as well as the wire should be given to any future appliances designed to achieve bodily tooth movement.

The values obtained for frictional force in this study in general tend to follow the first "classical" law of friction which states that "friction is proportional to the load applied"[1]. A range of values was determined, when reading the frictional force from the graph recordings, to give an estimate of the variation and measurement error. This range, which averaged from ± 5 grams at 63 grams load to ± 20 grams at 1032 grams, is probably an overestimate of the error of the method. At least eight friction readings were made on the graph paper for each force load and the readings are quite uniform (Fig. 5), therefore, the differences in frictional forces obtained probably tend to be more real than a range overlap would indicate.

The vibrating friction used in this investigation, was found to be somewhat less than static friction, but the actual mechanism which exists in the mouth is probably much more efficient in reducing friction. The forces of mastication against solid foods should produce considerable vertical and lateral movements of the teeth which could act to overcome the friction in a bracket.

The findings of higher friction values for saliva were surprising. It has been expressed in the literature that saliva may act as a lubricant to reduce friction in orthodontic appliances.[24] If the results of this study are valid, an explaination of the action of saliva in increasing friction could be based on the inherent friction present in any viscous fluid[1] providing added friction to two realtively smooth surfaces with low friction coefficients. The higher friction values obtained for oil at lower loads tends to support the above explaination. With relatively low force loads and low friction materials the lubricants (oil, grease, or saliva) provide more internal friction to the systems than they help to overcome. At higher loads, as the findings for oil tend to show, more friction between the surfaces develop and the inherent friction of the lubricant becomes less important, relative to the large friction between the materials.

The findings from the evaluation of friction in the edgewise appliance tend to oppose the view[19-21] that clearance between bracket and arch wire are important in decreasing friction. A more important consideration in the production of friction would seem to be binding of bracket edges onto the arch wire.[22] This can occur more readily with small wires. Wide brackets are an important factor in reducing binding by allowing less tipping on the arch wire. Tight ligatures increase friction, however, the length of time they remain tight in the mouth is open to question.

When force is placed on teeth by an appliance, friction is probably produced in the appliance - still the teeth move. Because teeth are surrounded by a vital environment, changes take place which constantly alter the nature of the force directed on the tooth. No known appliance can be expected to deliver a constant force to a tooth. By the same reasoning, a frictional force which exists on a testing board on the laboratory bench cannot be expected to duplicate the changing force of friction which exists in the mouth.

SUMMARY AND CONCLUSIONS

This study was initiated to test frictional forces in an experimental tooth moving appliance designed to equate the rate of biologic response of a tooth to applied force. A laboratory test of friction produced the following results:

1) friction was roughly proportional to load,
2) vibrating friction was slightly less than static friction,
3) saliva increased friction slightly,
4) binding of bracket edges on wire caused high frictional values.

A test of maximum tipping which could occur was performed on the experimental appliance. Deflection values obtained ranged up to 2.2 mm. for heavy loads.

The nature of friction is not well understood. Differences of opinion exist on the importance and action of friction in orthodontics. Most available discussions of friction are based on theory. Emphasis should now be directed to the testing of these theories.

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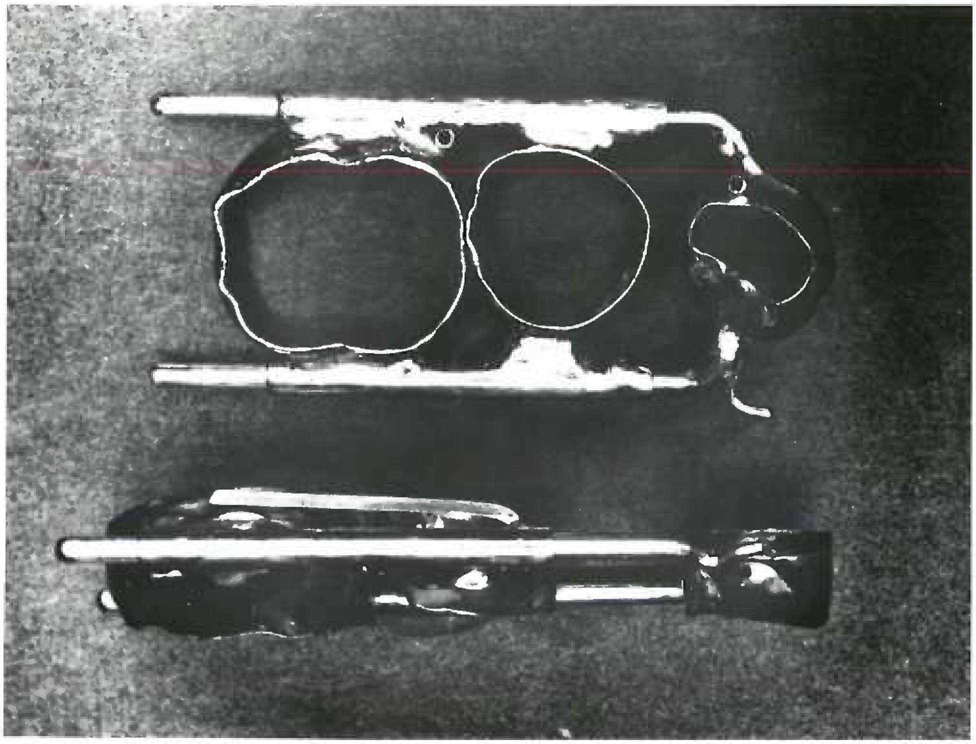


Figure 1. Experimental tooth moving appliance.

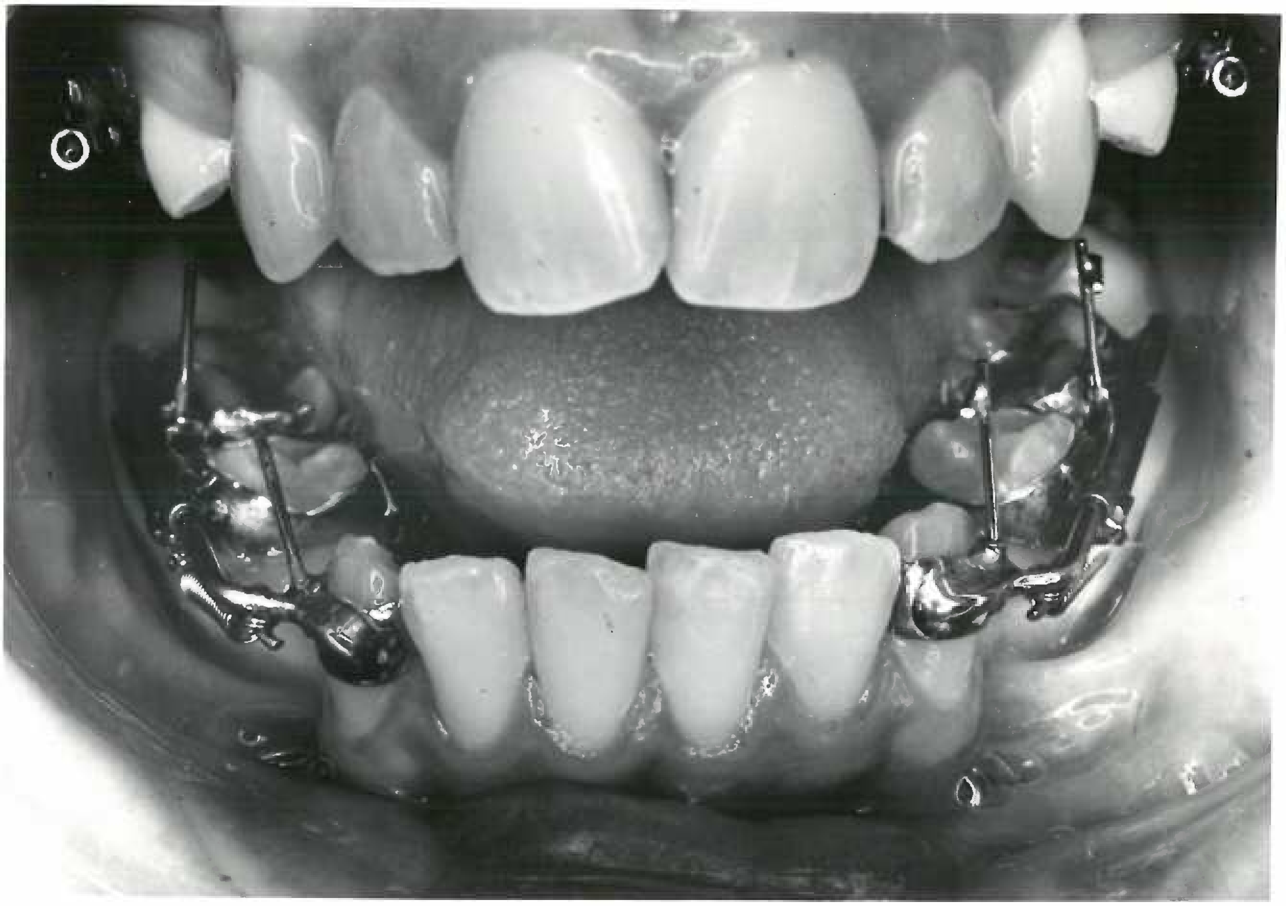


Figure 2. Appliance in the mouth.

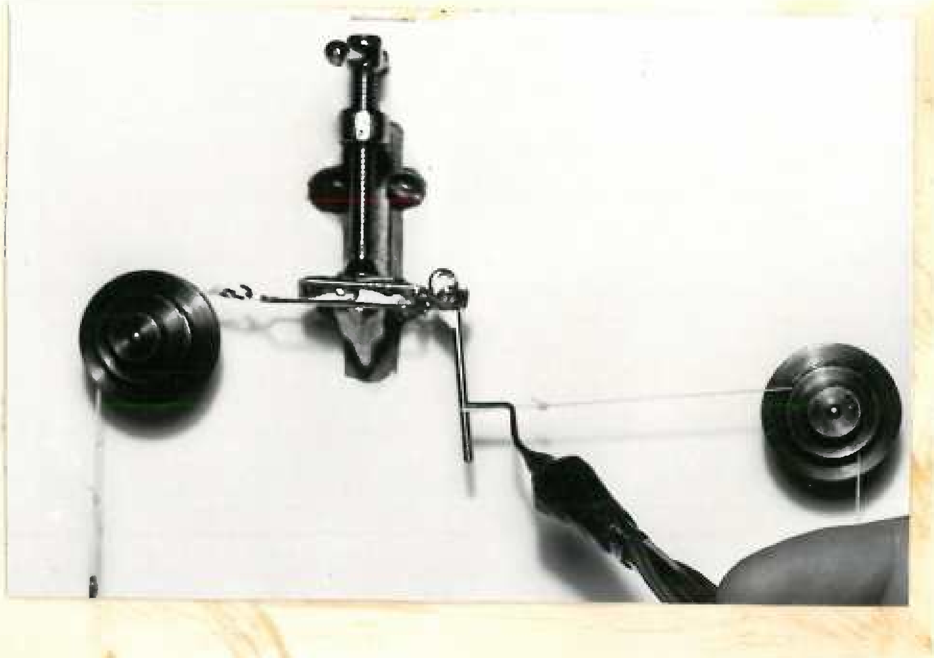


Figure 3.

Apparatus for testing friction in experimental appliance, showing place of application of force with dynamometer to reduce load on one side.

Figure 4.

Calibration of dynamometer

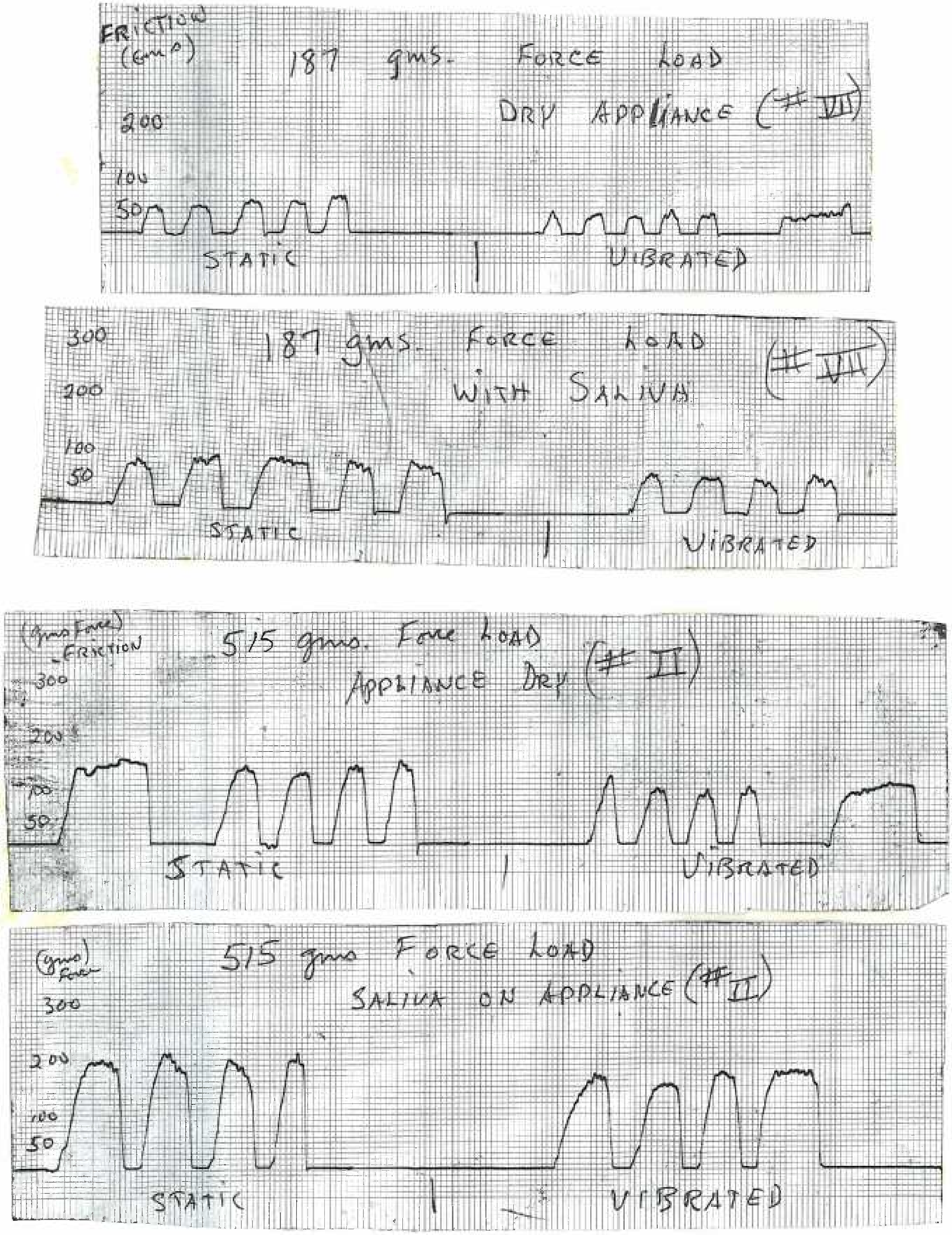


Figure 5. Sample graph recordings of friction values on dry and saliva saturated appliances.

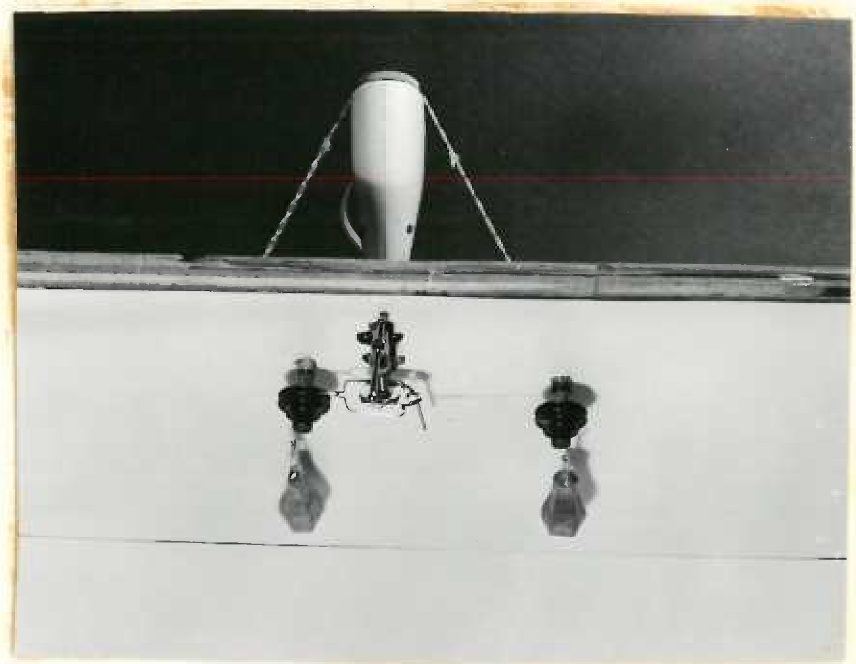


Figure 6. Friction testing apparatus with vibrator.

Figure 7. Apparatus for testing the edgewise appliance.

TABLE I

Mean deflection values (mm.) for the experimental tooth moving appliance.
(n = 2)

Force (gms.)	Crown	Apex	.072 wire	Apex (adj.)	Apex (comp.)	Apex (from band bending)	Band % bending
63	.075	.175	.016	.159	.158	.001	0.6
187	.192	.539	.047	.492	.405	.087	17
328	.292	.904	.082	.822	.616	.206	25
515	.404	1.330	.160	1.170	.853	.317	26
747	.548	1.944	.218	1.726	1.157	.569	33
1032	.679	2.590	.303	2.287	1.433	.854	37

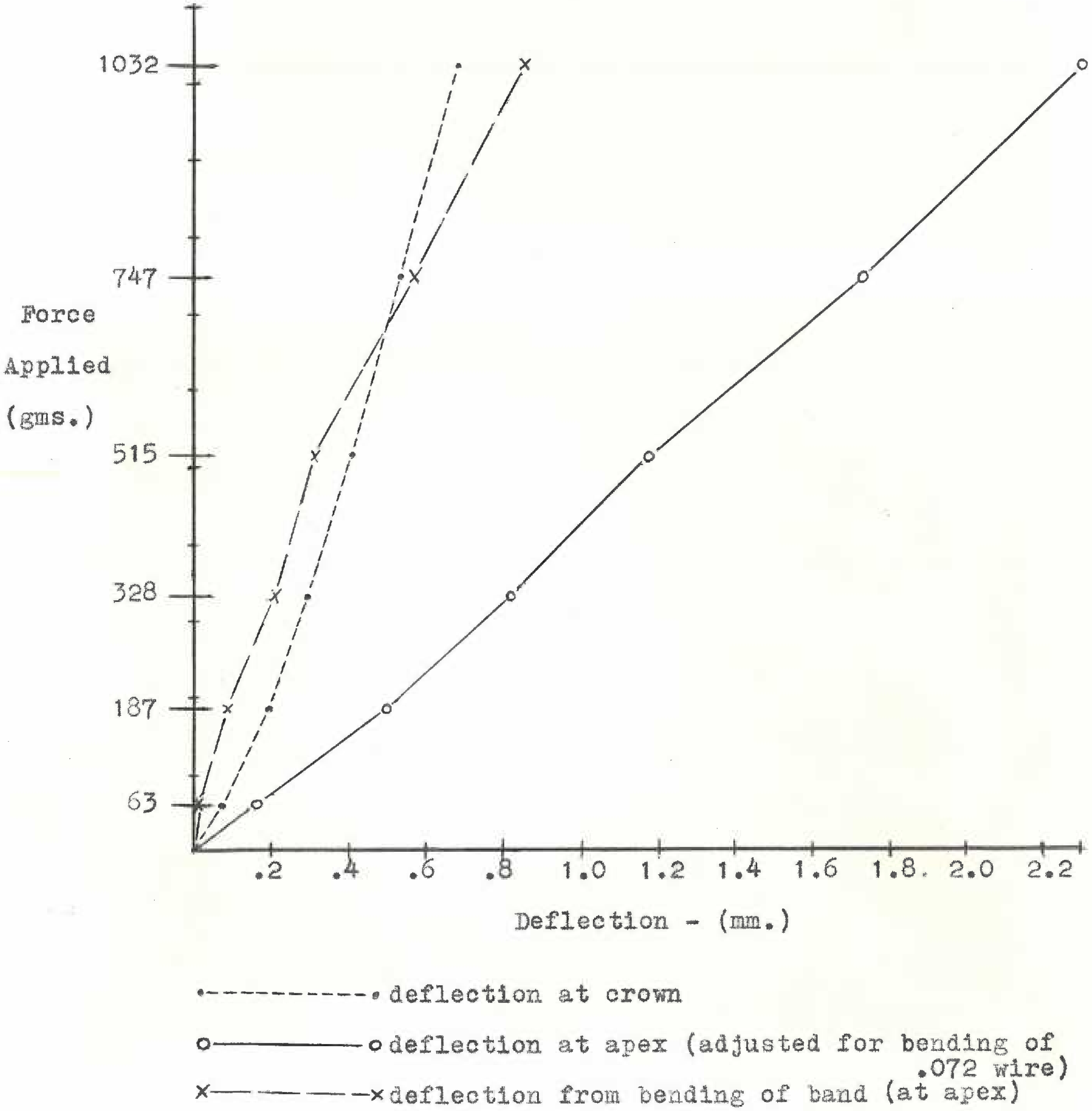
TABLE II

Mean friction values (gms.) for the experimental tooth moving appliance (μ = coefficient of friction).
(n = 6)

Force (gms.)	Static	Vibrated	Range(±)	μ(stat.)	μ(vib.)	% reduction in μ by vib.
63	26	12	5	.405	.196	51
187	50	35	8	.268	.184	31
328	92	65	10	.280	.197	30
515	137	112	15	.266	.218	18
747	229	190	15	.306	.254	17
1032	350	306	20	.339	.296	13

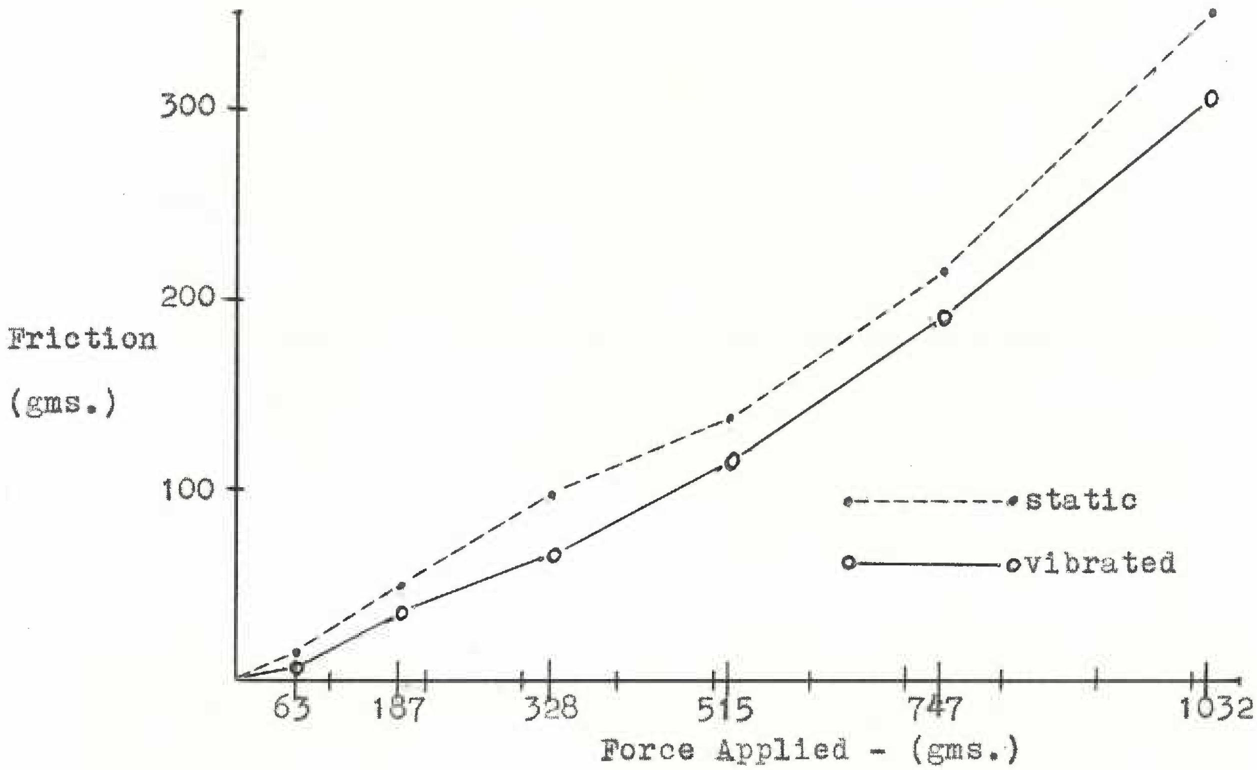
G R A P H 1

Deflection of Appliance (mm.)

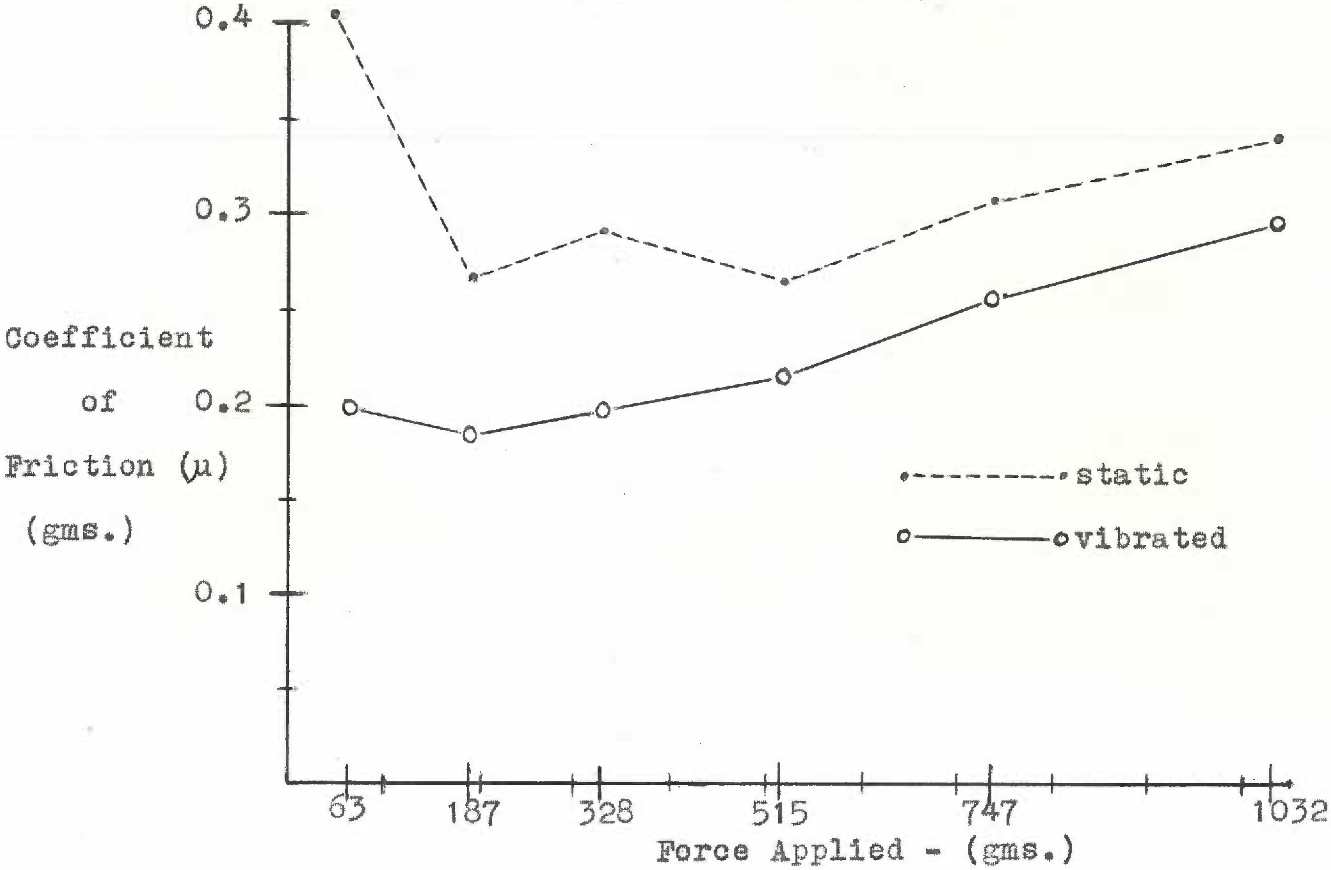


GRAPH 2

Friction



GRAPH 3 - Friction



T A B L E III

Friction with Saliva

STATIC

Force (gms.)	Dry	Saliva	μ Dry	μ Saliva	% increase in μ with Saliva.
63	20	54	.325	.850	162
187	51	88	.273	.471	73
328	76	135	.234	.412	76
515	122	182	.238	.353	48
747	188	275	.251	.368	47
1032	308	405	.298	.393	32

VIBRATED

63	12	30	.192	.469	144
187	35	62	.187	.329	76
328	55	102	.168	.313	86
515	100	158	.194	.306	58
747	159	248	.213	.332	56
1032	262	390	.226	.378	67

Mean friction values (gms.) for the experimental tooth movement appliance dry and saturated with saliva (n=2).

GRAPH 4

Mean values for friction in the experimental appliance tested dry and saturated with saliva (n = 2).

(static friction)

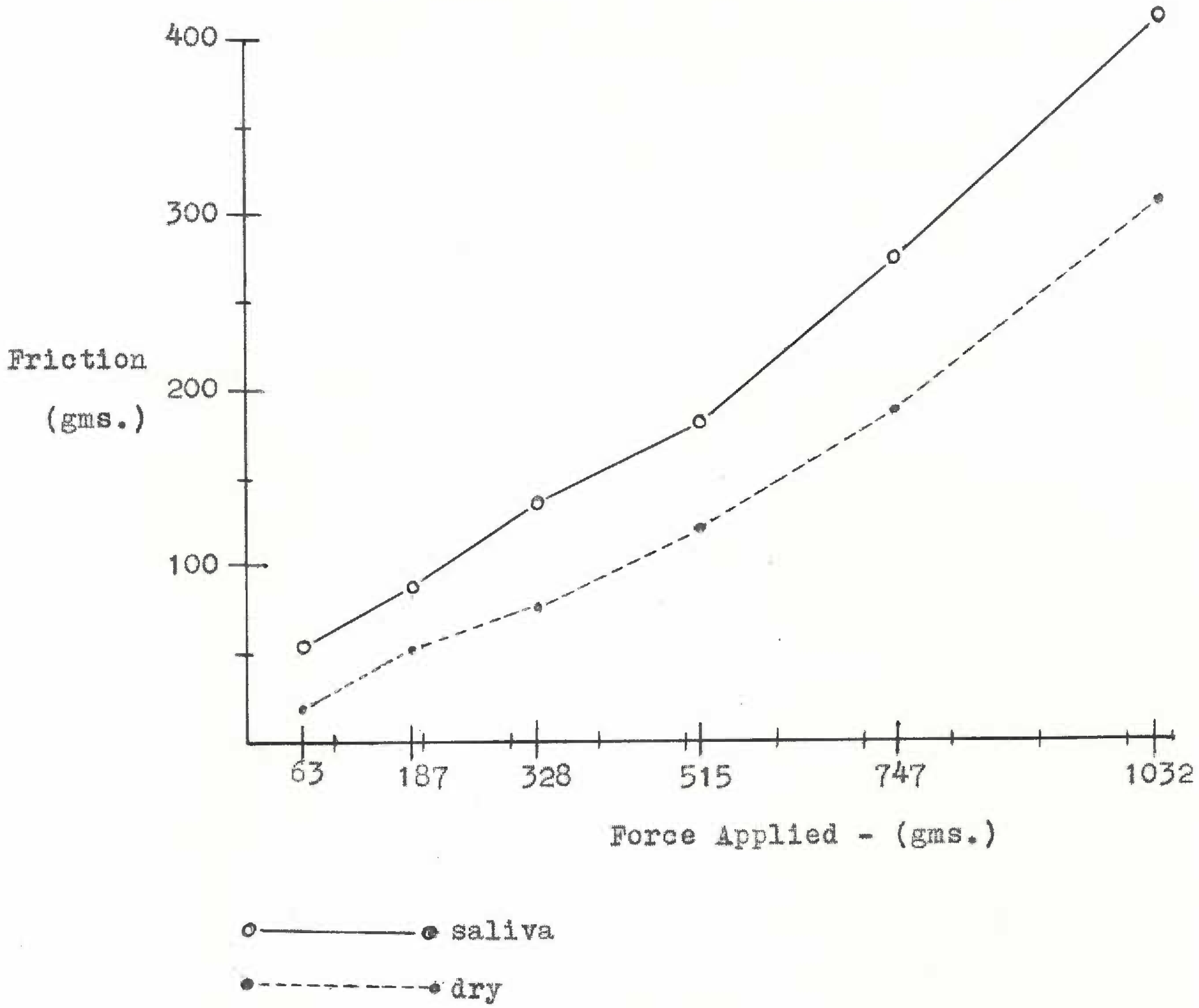


TABLE IV

Mean friction values (gms.) with clean, dry experimental tooth moving appliances compared with the influence of a heavy grease and a thin oil.

	STATIC			VIBRATED		
Force (gms.)	Dry	Grease	Oil	Dry	Grease	Oil
63	20	55	40	12	45	18
187	51	78	60	35	68	38
328	76	118	88	55	95	70
515	122	180	125	100	150	110
747	188	250	172	159	232	140
1032	308	395	265	262	345	235