THE UNIVERSITY OF MANITOBA

AN INVESTIGATION INTO THE THREE-DIMENSIONAL FORCE AND MOMENT CHARACTERISTICS OF SELECTED CUSPID RETRACTION MECHANISMS

by

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ABSTRACT

The present work was undertaken to investigate the three-dimensional force and moment characteristics of selected, commonly used, cuspid retraction loops. Six retraction loop designs were included in the investigation.

The examination of the forces and moments was performed using a mini-computer coupled to a three-dimensional measuring instrument developed at the University of Manitoba. The analysis of the data made use of slope relationships in order to compare the performance of the retraction loops to an "ideal" set of criteria.

The analysis of the results, suggested the following conclusions.

(1) The modified measuring instrumentation provided accurate three-dimensional data on the force and moment characteristics of cuspid retraction loops during activation.

(2) The use of slope relationships provided an easy means of viewing the results in terms of their orthodontic performance. The use of slopes was possible due to the straight line relationships that existed between activation and forces and moments.

(3) All loops as tested exhibited behaviour that was far from the translation ideal.

(4) Little difference, aside from the force-deflection rate was found between the loops.

(5) The incorporation of anti-tip and anti-rotation preactivations introduced a separate independant force system to that which already existed.

(6) Vertical misalignment of retraction loops resulted in the generation of unexpected, but clinically significant, forces and moments.

(7) Placement of the vertical portion of the loop closer to the cuspid resulted in an extrusive force arising during activation. This did not occur if the vertical portion of the loop was centered.

DEDICATION

THIS THESIS IS DEDICATED TO

THE MEMORY OF MY LATE

FATHER, ALLAN LACK

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Table of Contents

List of Figures

List of Tables

INTRODUCTION

Many techniques have been advocated for the retraction of cuspids in orthodontic cases requiring the extraction of bicuspids. Most of the techniques have arisen as a result of a clinician's personal preference with little scientific data being given to support any claims.

In those cases where individual cuspid retraction is utilized, the cuspid retraction must be completed prior to the retraction of the anterior segment. The ability of a retraction loop to produce the desired movement may therefore be a decisive factor in determining treatment time.

In most clinical situations, the distal movement of the cuspids is ideally one of pure translation, with no tipping or rotation of the tooth occuring. The ability of a retraction loop to produce pure translation can therefore be taken as a measure of how good a retraction device is.

For a retraction device to be able to produce pure translation, it must be able to generate a force in the distal direction, with no force in the buccal-lingual or occlusal-gingival direction. There must also be no rotations occuring about any of the three axes. To accurately assess the performance of a retraction loop, three-dimensional measurement of the forces and moments produced by the retraction loop during activation is required. This three-dimensional assessment can then be used in an evaluation of how successful the generated force system might be in producing pure translation.

The purpose of the present investigation was to measure the force characteristics of selected cuspid retraction loops, using equipment capable of simultaneously measuring the three-dimensional forces and moments generated by each loop during activation, and to use this information in a comparison of the retraction loops to the ideal.

REVIEW OF LITERATURE

INTRODUCTION

The practice of orthodontics, makes use of the application of forces to a tooth in order to initiate the proper biological response that produces the movement of the tooth.

Since the advent of orthodontic procedures, the clinician has been faced with the problem of not knowing with any certainty how much force was being applied to a tooth, or group of teeth, by means of the appliances being utilized. Richmond as early as 1933 stated "It seems that so far orthodontists have known only two pressures, viz. excessive and mild and have never been able to define either". This problem of assigning values to the force delivered by orthodontic appliances is one that has never been adequately solved and still plagues the orthodontic profession.

The mechanisms of assessing such a force system fall into three main categories, as listed by Teasley in 1963:

(1.) physical measurement,

(2.) the use of mathematical formulae,

(3.) a combination of the above two methods.

PHYSICAL EVALUATION OF ORTHODONTIC FORCES

As reported by Paulich (1939), a German orthodontist by the name of Borschke (1920) was perhaps the first individual to develop an instrument designed purely for measuring orthodontic forces. This instrument was designed to be used intraorally, and consisted of two pieces of "Wipla" stainless steel wire clamped in a small tube. The wires were parallel to one another and of unequal length. A force of 20 grams was capable of deflecting the longer end 2 millimeters from the shorter end. The operator was able to calculate the force generated by a finger spring by placing the longer end of the instrument between the finger spring and the tooth. If the distance between the shorter and longer ends of the instrument was 2 millimeters when the finger spring was brought to its preactivated position, the pressure applied by the finger spring did not exceed 20 grams.

Irish in 1927 described a device known as the Irishometer, based on the principle of the calibrated spring balance, which was utilized to investigate the "pressure" delivered by othodontic springs. The device was designed to be used in laboratory studies. Irish makes little reference to his results, but from the photographs in the article, it appears that he was measuring forces produced by gold wire auxiliaries, and that the forces were in the range of 80-140 grams (3-5 ounces).

Nowack in 1931 utilized a calibrated spring balance to examine finger springs. Paulich (1939) reported that Nowack was able to establish that forces up to 700 grams could be exerted by a cantilever finger spring 5 millimeters in length displaced 1 millimeter.

Another German orthodontist, Bendias constructed a device called the "Regumeter" in 1931. According to Paulich (1939) the instrument was capable of measuring forces delivered by an appliance in compression as well as in tension. The instrument was able to measure forces on a model as well as intraorally but Paulich makes no mention of any data generated by the use of it.

In 1933 Peyton and Moore were able to measure the displacement of a straight cantilever spring when loaded with weights. The spring being tested was supported at one end in a pin vice. At a measured distance from the pin vice, a small basket, in which weights were placed was attached to the spring. The deflection of the spring was determined to within 0.1 mm. by using a travelling microscope with a cross hair reference line. Peyton and Moore using gold wire of .018, .020, .022, and .030 inches in diameter concluded that the maximum pressure from a simple cantilever spring was seldom above 60 grams and more generally fell within the range of 2 to 25 grams.

Richmond in 1933 developed a gauge capable of measuring the "stress" and "strain" generated by orthodontic devices both in "vivo" and in "vitro". Richmond utilized this gauge in a laboratory investigation of the forces developed when a ribbon archwire was tied into various malposed teeth. He found that the forces developed by the arch were sometimes in excess of two pounds (907 grams) of force per tooth. This gauge is still utilized by orthodontists today for measuring the forces developed in the mouth by appliances.

A device developed by Wirt in 1935 enabled him to measure the force applied to each tooth when they were tied into an alignment arch. The purpose of this device was to allow the operator to adjust the alignment arch prior to its insertion in the mouth, to prevent excessive (not defined by him) forces from being used.

In 1937 Brumfield built a mechanical model (based on the mathematical model suggested by Sved (1937)) to measure the reaction of the teeth in one direction when the archwire was deflected 1/100 of an inch. The device agreed closely with Sved's mathematical prediction, and showed that when an .022 x .028 inch gold-platinum archwire was deflected 1/100 of an inch, forces as high as 2.5 pounds (1134 grams) could be generated.

Paulich in 1939 measured the forces developed by rubber bands and round labial archwires using the instruments developed by Bertram (1931) and Irish (1927). He found that 10 millimeter elastics stretched three times their original length would produce a force of 311 grams. In comparing .032 inch labial archwires of gold-platinum and stainless steel, Paulich found that when expanded 10 millimeters the gold-platinum archwire produced 42 grams of force while the stainless steel wire when expanded the same amount produced 86 grams of force.

In 1952, Storey and Smith in a classical paper, studied various sizes and types of springs, using weights for loads, and an optical micrometer for measuring displacement. The experimental situation was similar to that described by Peytồn and Moore in 1933. From this investigation, they were able to conclude that the retraction springs which were popular at that time applied high forces (in excess of 500 grams) with small deflections (2-3 millimeters), and that the intensity of the force decreased markedly as the tooth moved.

Burstone et al in 1961, studied the load-deflection characteristics of various springs made of stainless steel, using an instrument which was capable of measuring both the load and the deflection of the spring at that load.

The authors pointed out that the characteristics of the spring could be changed by altering four factors:

(1.) the wire alloy and therefore its mechanical properties,

(2.) the cross sectional geometry of the wire,

(3.) the configuration of the spring,

(4.) the direction in which the spring is activated.

The authors studied these factors, utilizing their instrumentation, to support their theoretical considerations. From their investigation, they suggested that the force characteristics of an appliance could be predicted by nonempirical methods.

Neuger also in 1961 using compression-tension gauges studied the forces generated by light torquing auxiliaries made of different diameter wire. He concluded that the forces produced by the auxiliaries were proportional to the fourth power of the diameter of the wire, thereby supporting Burstone's conclusion concerning the effect of the cross sectional geometry on the force production of a spring.

The above early attempts to measure forces produced by orthodontic appliances all utilized mechanical systems to measure the forces produced when an appliance was activated. These were two dimensional measurements of the load deflection characteristics of the appliance which did not consider any forces generated in the third dimension, or the moments which arose as a result of these forces.

Burstone (1962) in Vistas in Orthodontics, describes two devices which represented his efforts to improve on the completeness of orthodontic force measuring methods.

One of the devices was a Water Torque Gauge (manufactured by the Water Manufacturing Company) which was used to mechanically measure the torquing action developed by an orthodontic spring. The other instrument consisted of an electronic micrometer to measure displacement, coupled to a spring balance which mechanically measured the forces developed by a given displacement. The instrumentation thus had the capabilities of measuring forces and displacement simultaneously and the capabilities of investigating torquing forces separately. The principle disadvantages of this arrangement lies in the fact that only one force and one rotation may be investigated in each experiment.

The advent of electronic components to measure forces and displacements meant an increase in the accuracy of measuring devices and a reduction in the human error that arises due to the tedious nature of reading and recording from mechanical gauges.

The first attempt to measure forces utilizing electronic components alone was by Johns in 1953. This work was further reported on by Halderson et al later in the same year. The measuring apparatus consisted of a transducer for converting the force to electrical energy, an amplifier, and an ink-writing oscillograph to record the force. Halderson et al studied the effect of varying the properties of orthodontic springs and also the relationship between deflection and the amount of force produced in stainless steel archwires of various diameter. The investigation was carried out in vivo. The archwire to be tested was ligated to all the brackets in the mouth, except the lateral incisor. The deflection necessary to seat the archwire in the lateral bracket was maintained at .020 inches while the diameter of the wires were varied from .006 to .020 inches. The tranducer shaft was applied to the archwire in the lateral incisor region, while the transducer was held by the investigator. The force required to seat the archwire was then measured and recorded utilizing the ink-writing oscillograph. They found that the forces developed by such a deflection tended to be large, varying from approximately 20 grams for .006 diameter wire to approximately 680 grams for .020 diameter wire.

In examining springs, they studied the effect of varying lengths and diameter of auxiliary springs on the amount of force which was produced. Using a fixed wire length, the authors found that a one millimeter deflection in an .016 wire produced a force of 22 grams, while the same deflection in an .020 round wire resulted in 92 grams of force. Using springs of similar diameter, the investigators discovered that a spring, 6 millimeters in length, produced 84 grams of force, while one 14 millimeters long, produced only 16 grams of force for the same amount of deflection.

Testing nine millimeter vertical loops of .0215 x .0275 inch wire, they discovered that opening the loops one millimeter resulted in 800 grams of force. This led them to conclude, that the force levels produced by this type of loop was excessive.

In 1973 Burstone et al make reference to a system that has the capabilities of measuring forces and couples acting on a tooth in the three planes of space. The measuring system made use of a force transducer arrangement. The transducer consisted of two semi-rigid bars to which strain gauges were applied to record bending, torsion, and axial loads. Beam theory and experimental loading were used for calibration. The authors make no report of any data generated by the above device and no further reference to this device could be found in the literature.

Solonche et al in 1976 describe a measurement system for determining the forces and moments delivered by an orthodontic appliance in an experimental situation. In this system, the appliance is considered to be uniplanar. The force is measured using a linear voltage displacement transducer (L.V.D.T.), coupled to a cantilever beam. The moments are measured by angular displacement tranducers. The displacement of the spring is measured by another L.V.D.T. coupled to a movable carriage allowing pre-determined activation to be carried out. The data is recorded on an x-y plotter as moment or force versus deflection. The sensitivity of the system was found to be greater than one gram for forces and five gram-millimeter for moments, and possessed a measurement error of less than 1%.

The first attempt found in the literature to measure orthodontic forces in three dimensions was that of Teasley et al in 1963. These authors designed and fabricated an instrument which was capable of resolving the force system for any appliance into six components, orientated along the bucco-lingual, disto-mesial, and appico-occlusal axes. These six components consisted of "three orthogonal rectilinear forces" and "three orthogonal angular forces or couples".

The device consisted of a denture plate assembly made up of a steel jig plate to which were attatched twenty-eight metal teeth in an arch form, a force sensing element made up of six strain gauges with a range of plus or minus 80 ounces (2268 grams), and an electrical control system with an amplifier for recording the forces produced. The system proved to be accurate to within two percent and was utilized by Teasley to look at the force system produced by second order bends as part of a preliminary investigation into the instruments accuracy.

This instrument was subsequently utilized by Buck et al in 1964 to investigate the force systems involved in various bracket archwire combinations in which there is a sliding action, with a coil spring supplying the force.

Teasley (1979) in personal communication with this author, pointed out that subsequent work was done with this instrument, but it does not appear to be reported on in the literature.

In 1978 Paquien described the development of an instrument that is capable of measuring simultaneously the three forces and three moments produced by an orthodontic appliance for each position of activation of the appliance. This instrument uses strain gauge force transducers and a minicomputer for the aquisition and interpretation of data collected by the instrument. The strain gauge tranducers of which there are six, are so arranged that the instrument can measure forces simultaneously in the three planes of space ie (x,y,z,) and also the moments around these planes. The instrument developed proved to be capable of measuring forces up to a maximum of 100 grams plus or minus 10% with a geometrical distortion at the maximum load of .2 millimeters. Due to problems encountered in the measurement of moments, they were not thoroughly tested, but were assumed by the author to be measurable up to a maximum of 2000 gram-millimeters plus or minus 10%.

Subsequent developments by McLachlan (1979) have corrected the problems encountered by Paquien. As a result of these developments, the instrument now has the capabilities of measuring in three dimensions, forces up to a maximum of 130 grams and moments to a maximum of 2300 gram-millimeters with an overall accuracy of plus or minus 3% of maximum reading.

The need to understand better the characteristics and quantities of forces and moments produced by the activation of orthodontic appliances can be seen from the above to have been of continuing interest to orthodontists for a great length of time. The early attempts that utilized mechanical gauges and two dimensional analysis fell short in their attempts due to the avoidance of the third dimension and also due to the inaccuracy of their early measuring techniques.

With the advent of more modern measuring techniques the accuracy of the measurements improved, but the lack of measurement in the third dimension made these results still incomplete. Only recently, with the use of electronic technology and computers, has it become possible to determine forces and moments simultaneously in all three planes of space.

MATHEMATICAL EVALUATION OF ORTHODONTIC FORCES

Numerous investigators have suggested that the application of sound mathematical and engineering principles should permit the direct calculation of the forces developed by orthodontic appliances due to activation, and hence any problems of measurement would be bypassed.

Fish in 1917 was one of the first individuals to comment on the need for an understanding of engineering principles in orthodontics. Fish stated in his article that by utilizing static analysis of appliances, better knowledge and understanding of the force system developed and the effects of these systems could be gained. Hanau, an engineer, also in 1917, stressed the importance of utilizing engineering principles in orthodontics.

Peyton and Moore in 1933 utilized a known engineering formula to calculate the pressure applied to a tooth by a cantilever spring. The formula utilized by them was $P=3EIy/l^3$, where:

y=displacement in inches

P=load in pounds

l=length of beam in inches

E=modulus of elasticity in lb/in↑2

I=moment of inertia in (inches)↑4

The results from their calculations, in which they studied the effects of varying wire diameter and the length of the cantilever, were found to be in very close agreement with the results they obtained from experimental measurements. This approach provided a good check on their method, and illustrated to them the applicability of mathematics to calculation of forces in simple cantilever springs.

Sved in 1952 utilized a new method developed by Brumfield called "The Solution of Statically Indeterminate Structures by Transmission

Coefficients". Using this approach, he attempted to analyize the force system developed in deflecting an archwire from its passive position, 1/100 of an inch into a bracket.

To accomplish this, he assumed that the arch was made up of a straight beam, supported at twelve points (representing the brackets on the teeth) along its length. He then assumed that for any of the calculations, the segment of the archwire being tested would be supported at its ends and would be 1/100 (0.254 mm.) of an inch away from the bracket in the middle of this span. He was then able to apply his calculations to determine the forces produced by deflecting this wire 1/100 of an inch, into the bracket. Using this calculation technique and studying .016 inch and .028 x .022 inch gold-platinum wire, he was able to conclude that .016 inch round wire exerted only 13 per cent of the force exerted by an .028x.022 inch archwire and that the forces generated by deviating an .028 x .022 archwire 1/100 of an inch may exceed two pounds (907 grams) of force.

Drenker in 1956 presented several mathematical equations which described the forces produced by second order bends. By utilizing this approach, Drenker was able to demonstrate that the resultant forces in the system produced a couple leading to intrusion of the teeth at one end of the segment and extrusion of the teeth at the other end. He also showed that "the torque received by either end tooth is about one half as great as the torque received by any other tooth in the segement".

Drenker also calculated that the forces produced by second order bends can be as high as two pounds (907 grams), and that the torque can be as high as .5 pounds-inch (5760 gm-mm.), but that these large forces become quickly diminished due to the small distance of activation of second order bends.

Waters in 1970 ultilized classical elasticity theory to study the force displacement relationship of two orthodontic springs ie. a finger spring and a buccal canine retraction spring.

The procedure involved in the analyis of the appliance is as follows:

(1.) breakdown of the appliance into component parts which are amenable for analysis,

(2.) the consideration of the shearing forces and bending moments necessary to maintain the equilibrium of each part,

(3.) the determination of the deformation of each component under the forces and couples required for its equilibrium under point 2,

(4.) the summation of the deformation of the component parts in terms of an arbitrary and externally applied force or load.

In order to check the resultant calculations, the load-deflection relationships of enlarged models of the two appliances were experimentally checked, and found to be in agreement with the calculated theoretical values within the accuracy of the experimental measurements.

Waters utilized the above procedure in 1972 to examine apron springs and cuspid retractors and concluded from his calculations that the flexibity of an appliance varied directly with the number of coils in the appliance and that it varied inversely with the diameter of the wire. He also concluded in his calculations that the cuspid retractor has a stiffeness approximately 15% lower than a comparable apron spring.

In 1976 Waters utilized simple beam theory to investigate the force system developed in plain archwires when they were displaced. From these investigations he concluded:

(1.) the wire is deformed elastically for small displacement,

(2.) the force applied to a misaligned tooth is directly proportional to the two wire parameters E(modulus of elasticity) and I(second moment of inertia of the cross section),

(3.) the forces applied to a misaligned tooth are directly proportional to the distance the wire has been displaced from its normal position,

(4.) if the misaligned tooth is lingually displaced, alternate lingual and labial forces of decreasing magnitude are applied at successive teeth in the arch.

Waters (1976) also using simple beam theory looked at the displacement characteristics of an archwire with vertical loops. In this investigation he studied the effects of varying the loop length and width and concluded:

(1.) an archwire with vertical loops is always more flexible than a straight arch providing the spans are the same length,

(2.) the flexibility for horizontal displacement is invariably greater than that for deflection in the vertical plane,

(3.) for horizontal displacement the length and the width of each loop are the most important variables influencing the flexibility such that the stiffness increased by 40% for every 1 mm. decrease in loop width.

Burstone et al (1973) used a computer program to compare results obtained from an experimental investigation to theoretical results calculated from the computer program. The computer program as reported by Koenig and Burstone (1974) is derived from an analysis first performed to determine the force and deflection characteristics of arbitrary curved beams such as the turbine blades in aircraft engines. They assume in their model that orthodontic appliances may be studied as complex generalized beams with large length to cross section properties.

They concluded that the computer program was largely predictive of experimental forces produced by orthodontic appliances. Some variation in prediction however arose as a result of friction between the wire and the brackets. They also felt that clinical force systems can be reasonably estimated using the program but due to the fact that no details on the technique employed in the computer program are given, it is difficult to evaluate these claims.

In 1974 Koenig and Burstone reported on an investigation that utilized the above computer program to investigate the force systems present in a lingual arch, a vertical loop, and a Burstone rectangular loop.

In examining the force system developed in the placement of an .030 inch lingual arch they found that on placement of the lingual arch, due to the distortion of the arch that arises as a result of its placement, a lingual force of 510 grams and a moment of 9860 gm.-mm. was developed on the molars.

In examining a vertical loop of .016 diameter wire, they found that small activations of the loop produced high forces ie. a 1.32mm. activation produced a 1040 gm.-mm. moment and a force of 506 grams on a cuspid.

A rectangular loop was also examined enabling them to conclude that a 5 millimeter activation of this loop, resulted in an intrusive force of 230 grams and a small moment of 250 gm.-mm. at the cuspid.

They also concluded that the force-deflection rate for the rectangular loop was smaller than that of the vertical loop.

Yang and Baldwin in 1974 described a mathematical analysis of a space closing spring based on finite element analysis utilizing a computer. Yang performed this analysis on a 10 millimeter vertical loop and on a retraction loop utilized at Indiana University. The vertical loop was idealized by 28 elements and the other retraction loop by 102 elements.

The results of this investigation showed that a 1/2mm. deflection produced a force of 227 grams and a bending moment of 942gm.-mm. in the vertical loops.

The Indiana retraction loop produced a force of 114 grams for 1mm. of displacement and a bending moment almost two orders of magnitude less than that produced by the vertical loop.

The above springs were investigated utilizing both the finite element analysis, and an experimental investigation, which showed close agreement between the two techniques. This led the authors to conclude that the finite element method should prove useful in analyzing new spring designs prior to clinical studies and also in studying the effects of changing the properties of the springs.

Grief et al in a paper given in 1978 introduced a three dimensional finite element computer program for the analysis of orthodontic force systems. The basis of the program is that an archwire may be thought of as a number of finite elements tied together at connecting nodal points. Each of the nodal points is defined by three deflections and three rotations, and associated force and moment equilibria.

This program was utilized in the study of several types of retraction springs and T-loops, but the results of this investigation are not reported .

The attempts above to describe force systems produced by an appliance have all been made utilizing non-empirical methods. The approach however poses some very real problems. The complex geometry involved in appliances makes analysis virtually impossible in all but simple cases. The utilization of finite element and similar numerical techniques involves non-exact solutions and judgement in their application becomes important. In addition, the amount of computation required to solve complicated orthodontic appliances in three-dimensions is large. Most authors seem to have simplified these problems by making numerous assumptions concerning the appliances eg. two dimensionality. The description of the appliance performance utilizing mathematical or numerical analysis is at best an approximation of the actual appliance performance and, in general experimental coroboration is desirable. It becomes evident therefore that an approach that experimentally determines the actual force characteristics of an orthodontic device is of more benefit than a mathematical approach. The results of theoretical elasticity however are of great value in predicting and understanding general trends in the experimental results obtained from orthodontic devices.

CUSPID RETRACTION TECHNIQUES

Cuspid retraction in cases involving the removal of first bicuspids has always posed a problem to orthodontists. Croome in 1963 stated that "cuspid retraction has always been a rather awkward phase in the treatment of an extraction case. Management of this tooth seems to dominate and other procedures must await their turn". The mechanisms and techniques for the retraction of cuspids are extremely varied having arisen with what seems to be a lack of scientific thought and testing.

Carey commenting on this problem in 1950 states that with the gradual acceptance of bicuspid extraction and the problem of closing space arising, "Gadgets and accessories were created by the score, some attatched to the arch, some to the brackets, and some to the bands. Each one was a temporary delight with an unhappy future. They protruded, jiggled, pinched, and made dental hygiene and the patient's happiness impossible. There were cleats, levers, springs, coils, loops, safety pins, and many other diabolical devices". This seems to be the situation with the development of retraction devices both in the past and even to some degree in the present.

The primary goal of any device that is utilized in the retraction of cuspids is to apply a distalizing force. The application of this force is at the bracket of the tooth, and is accomplished generally by the use of coil springs, elastics, auxiliary springs used in conjunction with an archwire, and springs directly incorporated into either a continuous or sectional archwire.

The following section will serve as an historical overview of the development of force generating devices for the retraction of cuspids. From this it will be seen that the development of retraction devices has been based primarily on the individual clinician's personal preference with, until recently, little scientific thought being given to their development.

Case in 1892 as reported by Pollock (1916) was perhaps the first individual to utilize the application of force to move cuspids. Case used intermaxillary elastics to distalize the lower cuspids following the extraction of the lower first bicuspids.

Arnold in 1928 described the first usage of a coil spring to close spacing between teeth. The coil spring became known as the

"Arnold spring", and although it was not utilized by him to distalize cuspids, this type of spring has been extensively utilized for the retraction of cuspids.

Erikson, also in 1928, described an auxiliary spring to be utilized to retract cuspids. The appliance consisted of an .020 triangular spring attached to the archwire distal to the cuspids. The spring formed an isoceles triangle (possessing a one and one half turn loop at its apex) with the archwire. The mesial leg of the triangle was soldered to the archwire distal to the cuspid. The distal (free) leg of the triangle was hooked at its end and engaged the distal end of the molar tube. To activate the spring, the distal leg of the triangle was bent mesially and then reinserted into the distal end of the molar tube, thereby activating the spring.

In 1941 Johnson described the use of his twin-wire appliance for the treatment of those cases involving the extraction of bicuspids. In this appliance, a push coil spring is the method of choice to move the canine distally. A coil spring of .006 wire is placed around the archwire between the bands of the lateral incisor and the canine. The length of the coil spring is slightly larger than the space between the lateral incisor and the canine. By inserting the coil spring between the lateral and the cuspid a force is exerted on both ends, pushing the lateral incisor mesially and the canine distally. In order to prevent mesial movement of the lateral incisor, class two intermaxillary elastics are used in the maxillary arch and class three intermaxillary elastics in the mandibular arch.

Tweed in 1941 in discussing cases in which he felt that extractions were necessary ie. bimaxillary protrusion, decribed a technique utilized by him for the distalization of the incisal segment, and the closure of the spaces created by the bicuspid extraction.

Tweed's technique involved the preparation of anchorage in the buccal segments, utilizing second order bends to distalize the crowns of the posterior teeth, so that they were more resistant to the closure force. To create this closing force, Tweed utilized a .021 inch round archwire with vertical loops in the region of the extraction spaces. To activate the closed vertical loops, a steel ligature was passed around the distal end of the molar band to a small spur soldered to the archwire in the region of the distal leg of the vertical loop. By tightening the ligature, the loop was opened creating a distalizing force.

In 1942 Lewis described an appliance based on Tweed's approach above with the slight modification being that the appliance was activated by passing a ligature from the distal of the molar buccal tube to a stop on the archwire mesial to the molar tube. To activate the vertical loop, the ligature was tightened, thereby opening it.

Carey in 1944 utilized a sectional archwire technique to retract cuspids. The technique described gave two different methods for retraction. Both methods use an .020x.025 sectional archwire that extends from the second molar to the second bicuspid. In the first technique the retraction force is supplied by the compression of a coil spring mesial to the cuspid, while in the second technique retraction comes about by activating a vertical loop in the sectional arch, distal to the cuspid.

Lewis (1950) described a modification to his technique involving the retraction of cuspids individually. The retraction is accomplished by using a .008 inch coil spring between the lateral and cuspid on an .021x.025 inch archwire. By compressing the spring, the cuspids were moved distally.

Bull in 1951 introduced his sectional archwire assembly for the retraction of cuspids. The sectional arch consisted of an .0215x.025 inch stainless steel wire extending from the mesial of the cuspid bracket to the last banded molar in the arch. Approximately 1.5mm. distal to the cuspid was a closed vertical loop incorporated into the sectional archwire. The dimensions of the loop as given by Joule (1960) are approximately 8mm. for the maxillary arch and 6.5mm. for the mandibular arch. The device was activated by opening the vertical loop, providing a distalizing force on the cuspid. Bull suggested that the loop be activated 1mm. every 3 weeks.

Smith and Storey in 1952, were perhaps the first individuals to apply some scientific reasoning to retraction devices. In response to their investigation of forces developed by cuspid retraction devices, they developed a new cuspid retraction mechanism based on their findings.

This retraction device was essentially a clock spring as described by Strang (1950) with the following modifications:

(1.) it was made of .020 inch wire,

(2.) the inside diameter of the coil was 1/8 of an inch with two and one half turns at the apex, (3.) the arms of the spring were .3 inches long.

These modifications gave the spring a low load-deflection rate and a low force value at maximum activation, two properties that Smith and Storey felt were lacking in other cuspid retraction designs. Activation was the same as for the Strang "clock spring".

Buchner in 1953 used a continuous .021x.024 in. archwire with stops mesial to the molars tubes for cuspid retraction. The distalizing force was provided by a closed coil spring auxiliary attatched at one end to the molar tubes and at the other end by a ligature to the cuspid. By tightening the ligature, the coil spring was opened , providing the necessary force. Buchner felt that the advantage of this technique was that the entire posterior segment would function as an anchorage unit. This technique was also used by Dewel (1956).

The Begg technique, first described in 1956 by Begg, made use of a light, resiliant, .018 in. continuous archwire with hooks placed in the archwire mesial to the canines. Retraction was accomplished by the use of light intra-arch elastics stretched from the hooks in the archwire to the distal ends of the archwire.

Shapiro in 1957 wrote about a technique known as the Northwest Technique, which was based on Tweed's principles. Distal movement of the canines in the lower arch was effected by the use of intercanine compressed coil springs using a continuous archwire. The lower anterior teeth except for the cuspids were not banded. In the upper arch, the maxillary canines were moved distally using a technique similar to that described by Johnson (1941).

Parrott in an article in 1958 comments on the use of the universal appliance (Atkinson 1931) in extraction cases. Retraction in this technique is accomplished using a tightly wound coil spring of .010 inch tempered wire. The mesial segment of the spring is attatched to the cuspid bracket. The distal end of the coil spring has a straight section, and is passed through the molar sheath.

The spring is activated by pulling the straight section of the coil spring through the molar sheath thereby opening the spring. A continuous archwire is used in this technique.

Goldstein in 1959 invented an elastic thread consisting of a rubber core, covered by a closely woven nylon thread. Retraction of a cuspid could be accomplished by tying the elastic thread around the canine bracket and the posterior buccal segment. By stretching the thread, a distalizing force could be applied to the cuspid.

Sorenson in 1960 made use of a sectional arch of .019x.028 inch stainless steel wire for cuspid retraction. The distalizing force was supplied by a clock spring mechanism developed by Strang (1950). The clock spring is made of .022 inch gold wire forming a coil 2 to 3mm in diameter with 1 1/2 turns. The coil is soldered to the sectional arch between the cuspid and the second premolar. The free end of the clock spring has a small eyelet and faces distally. The spring is activated by passing a ligature from the eyelet on the spring to a staple on the canine band. By tighening the ligature, the spring is activated producing the desired force.

Burstone in 1961 utilizing basic mechanical principles designed a retraction spring that was capable of producing a low load deflection rate, a more constant release of force, and a low force value at maximum activation. This was in contrast to the various retraction mechanisms being utilized at that time eg. vertical loops.

The retraction device was made of flat .008x.020 inch stainless steel wire (flat wire was employed because of its optimal cross section for unidirectional bending). The spring was essentially a vertical loop with the following modifications. Since the maximum bending moment in a spring of this design is at the apex of the spring a coil 3mm. in diameter with two and one-half turns is incorporated at this point. At the junction of the horizontal and vertical legs are two helices, a small helix (diameter 1.5mm.) with one and one-quarter turns , and a larger helix (diameter 3mm.) also with one and one-quarter turns. These helices are utilized to compensate for angular deflection of the spring's horizontal legs as it is loaded. The spring is attatched between an .021x.025 inch base archwire and an anterior segment by a rectangular washer. To activate the spring, the washer is slid along the base arch and crimped at the desired activation.

In 1966 Burstone described a retraction device designed for individual cuspid retraction. The device was based on his segmented arch technique. The cuspid retraction mechanism consisted of two parts, the posterior stabilizing segment, and the cuspid retraction spring. The cuspid retraction spring is fabricated of .010x.020 inch wire and is 6mm. high. The spring is attatched to the posterior segment by a rectangular washer. The spring is rectangular in shape, with helices placed at the corners. The gingival helices contain one and one-quarter turns while the two occlusal helices contain two and one-quarter turns. The anterior arm of the spring is laminated and will orientate into the cuspid bracket. The mechanism is frictionless ie. not utilizing a continuous archwire. Because it is frictionless, all the necessary forces and moments must be incorporated into the spring mechanism itself for "complete" cuspid control.

Four major activations are therefore placed in the spring, which Burstone felt gave complete control over the cuspid movement. These activations are a distal force, an antirotation moment, an antitip moment and an intrusive force. The advantage of this type of retraction mechanism, Burstone felt, was good control over undesirable tooth movements, low load deflection rate, low force level and a constant force rate. The spring was activated 7mm. producing a force of approximately 200 grams.

In 1964 Broussard et al in an attempt to design a more efficient treatment system developed an appliance that utilized numerous auxiliary spring mechanisms. The rationale behind the use of auxiliary springs was:

(1.) they are easy to utilize,

(2.) the main archwire is continuous and therefore contained no bends ie. multiloops, which were difficult to incorporate and produced unpredictable forces,

(3.) patients are more receptive to the auxiliaries, than to a multilooped appliance.

The cuspid retraction auxiliary is made of either .014, .016, or

.018 inch wire, which is heat treated. It consists of a lock loop, a vertical post behind the lock loop, a vertical closing loop with a helical coil behind the vertical post, and a straight distal arm which was long enough to extend to the distal of the molar tube. The legs of the vertical closing loops were approximately 6mm. long.

To activate the loop, the vertical post is placed in the vertical slot in the bracket with the closing loops pointing gingivally. The distal arm was bent around the distal of the molar tubes such that the vertical arms of the closing loops were crossed thereby activating the spring. The lock loop is placed around the archwire securing the assembly. At the above amount of activation, the authors felt that the spring in .014 wire would be exerting 2 to 3 ounces (57 to 85 grams) of force. In order to obtain distal root movement using the retractor a moment is placed on the cuspid to produce the desired movement. This is accomplished by bending the vertical post distally thereby placing a moment independent of the spring's activation on the cuspid.

Gawley in 1971 utilized a similar auxiliary for canine retraction using the universal appliance of Atkinson (1931). The retraction mechanism in this case was constructed of .016x.016 inch square wire, with a sectional .014 inch wire between the second premolar and molar.

Hixon in 1972 attempted to provide a scientific argument for his orthodontic technique which was based on simplified mechanics. In this technique the cuspids are retracted on an .016 or .018 inch flat archwire with the distalizing force coming from plastic ligatures placed labially and lingually to prevent rotation. The flat arch due to its geometry tends to resist tipping motion of the cuspids.

The chief advantage of this approach as pointed out by Hixon is its simplicity. The technique does not make use of closing loops at the extraction sites, and hence minimizes the tendency for the arch to sag, which would allow the teeth to tip.

Andrews in 1976 explained the use of his straight wire technique in extraction cases. This appliance makes use of brackets that allow for active control of teeth in three planes of space ie. the brackets contain refinements that produce first, second, and third order movements. The extraction series brackets for the cuspids also contain antitip and antirotation capabilities. The cuspid bracket is designed with a hook, pointing gingivally extending from the bracket known as a "Power Arm". The purpose of this extension is the placement of the forces closer to the centre of resistance of the tooth. The retraction forces for the cuspid are supplied by either coil springs or elastics extending from the distal of the molar to the "Power Arm". The appliance therefore has the capabilities of offsetting the undesirable movements that arise as a result of applying a force to the crown of a tooth ie. rotation and tipping, as is seen in conventional mechanics.

Bench et al in 1978 described Rickett's Bioprogressive technique. This approach is based on the concept of applying light continuous forces. The brackets are such that they offer the possibilities of control in three diminsions ie. first, second, and third order capabilities are built into the brackets. The techniques uses sectional arches. The retraction sections are made of .016x.016 inch "Elgiloy" wire and extend from the cuspid through the molar tube.

The mandibular cuspid retraction spring is composed of a "double, vertical, helical, closing loop", placed distal to the cuspid in the extraction space. The distal end of the spring is placed through the molar tube and the bicuspid bracket. By pulling the distal end, through the molar tube, the spring is activated. The suggested activation is 2 to 3mm., producing approximately 150 grams of force.

The maxillary cuspid retraction spring is a "double, vertical, helical, extended, crossed T, closing loop". The mechanism is activated in the same fashion as the mandibular mechanism, but the activation is in the 3 to 4mm. range, producing a force of 150 grams.

CONCLUSIONS

A sound understanding of the force characteristics of orthodontic devices has been advocated by early dental researchers. Fish (1917) and Hanau (1917) both felt that it was imperative that the orthodontist have some idea as to what types of forces his appliances were producing during activation. The difficulty of this problem at that time was that the early reasearch methodology only allowed two dimensional measurements of force production from very simple appliances eg. coil spring. The type of measuring apparatus utilized was also relatively inaccurate and had no capabilities for measurement of moments.

With the advent of more modern measuring instrumentation eg.Burstone (1962) it became possible to measure force production more exactly and also to begin measuring the amount of moment generated during appliance activation. These attempts were still, however, only two dimensional, and the experimental technique required tedious physical reading of force gauges.

As technology improved, and the use of electronic components became more widespread (Johns 1953, Teasley 1963, Burstone 1973, Solonche 1976, Paquien 1978), it became possible to eliminate the physical reading of force gauges and to perhaps increase the accuracy of measurements. This use of more modern electronic technology also allowed measurement of both forces and moments.

As the technology continued to improve, it became possible with the help of computers to begin investigating the third dimension, (Paquien 1978), such that today the instrumentation is available to allow one to look at the force and moment production of orthodontic devices in three dimensions.

Due to the fact that sound mechanical principles have not until recently been utilized for the development of retraction devices, it is not surprising that their development has been somewhat haphazard. The evolution of retraction devices seems to have arisen with little or no scientific thought. A clinician simply decided that his method was superior with no experimental investigation, and touted it as the best possible way of accomplishing retraction. If the technique did not perform as promised, it was either discarded or else another loop or coil or wire was added to produce the new improved variety which would "undoubtedly" be superior. There was never proof given to support these claims.

More recent attempts by reaserchers (Burstone 1966, Broussard 1964, Bench 1978) to improve cuspid retraction devices have used more sound mechanical principles, but even today the claims of these researchers do not seem to have been substantiated by simultaneous, three-dimensional measurements.

MATERIALS AND METHODS

INTRODUCTION

The instrumentation (general view figure 1) used in this investigation was that originally developed by Paquien (1978), and modified by McLachlan (1979). It consisted of three principal components:

(1.) a measuring system,

(2.) a data aquisition system,and

(3.) a minicomputer.

MEASURING SYSTEM

The measuring system makes use of six transducers, arranged in a geometrical configuration which permits the computation of three forces, and three moments by a "linear combination of the six transducer responses." (Paquien 1978).

Figure 2 illustrates the relationship of the three forces and three moments, to the measuring instrumentation. These six components are:

(1) force in the x direction, (Fx): force in mesial-distal direction,

(2) force in the y direction, (Fy): force in occlusal-gingival direction,

(3) force in the z direction, (Fz): force in buccal-lingual direction,

(4) moment around the x axis, (Mx): rotation around the mesial-distal axis,

(5) moment around the y axis, (My): rotation around the occlusal-gingival axis,

1. Measuring system
2. Data aquisition system
3. Minicomputer

Figure 1. General view of instrumentation

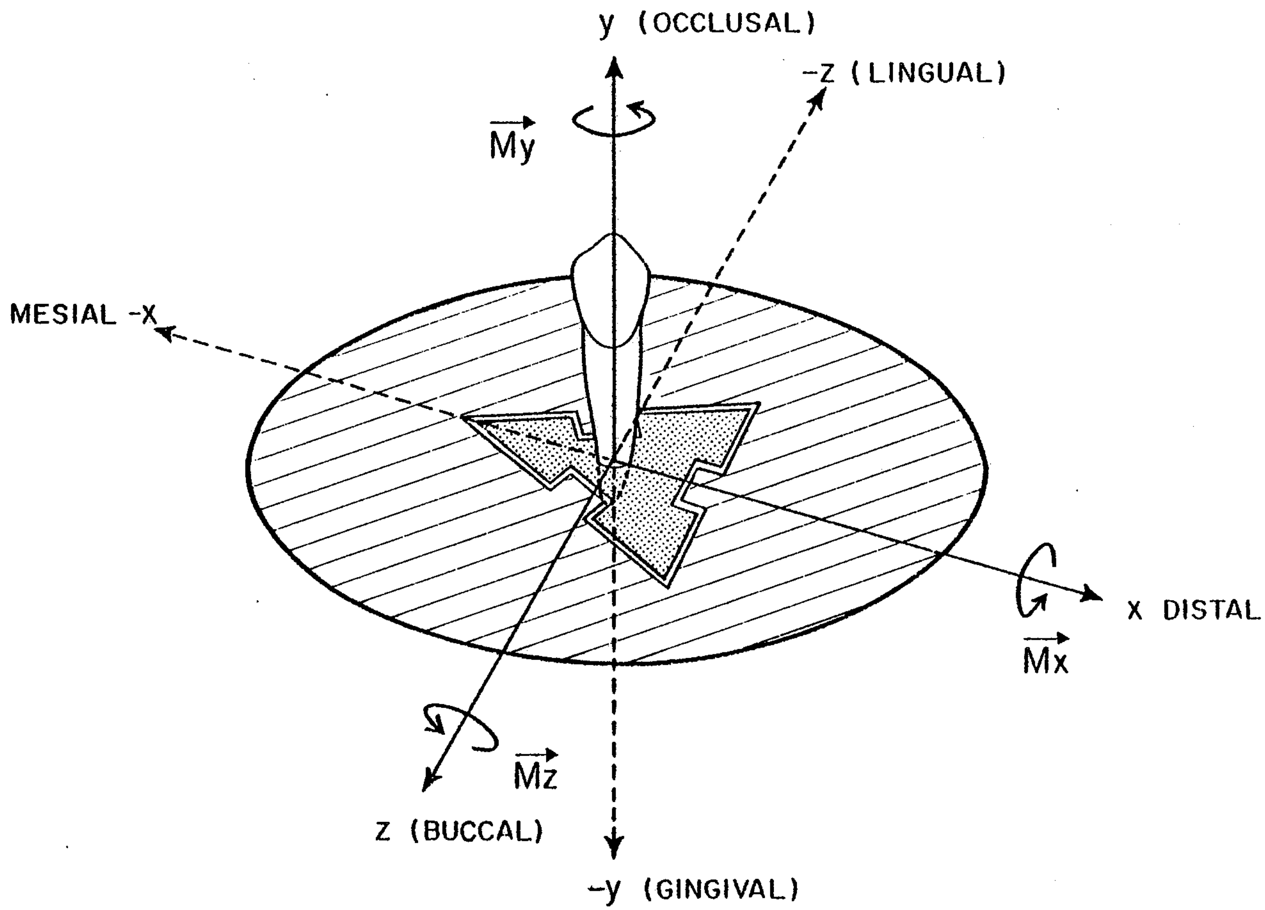


FIGURE 2. RELATIONSHIP OF THE THREE FORCES AND MOMENTS TO THE MEASURING INSTRUMENT

(6) moment around the z axis, (Mz): rotation around the buccal-lingual axis.

The x,y,z, axes of the instrument may also be readily aligned to other dental axes, if required.

The transducers consist of two strain gauges cemented to a cantilever, such that the transducer is sensitive only to bending. The strain gauges are mounted in a constant voltage, four-arm, Wheatstone bridge (fig. 3A) allowing a change in resistance of the strain gauges to be converted to an electrical signal.

The Wheatstone bridge method leads to the derived formula:

$$U = Vb - Vd \quad (1),$$

where U is the output voltage. If the cantilever is subjected to bending strain, Rt becomes Rt + ΔR and Rb becomes Rb − ΔR (fig. 3B) and leads to the equation,

$$Vd = Vb + Vb\Delta R/R \quad (2)$$

if this is substituted into equation 1 we end up with

$$U = Vb\Delta R/R ,$$

and from this it can be seen that the output voltage is proportional to the change in resistance of the strain gauges. This in turn is proportional to the amount of bending of the cantelever which is proportional to the applied force. Thus, with the application of proper constants the output of the strain gauge transducers can be read directly in terms of grams of force.

The measuring instrument (fig. 4) consists of four main parts the frame, an internal suspended ring, a central triangular block, and an electromagnetic vibrator.

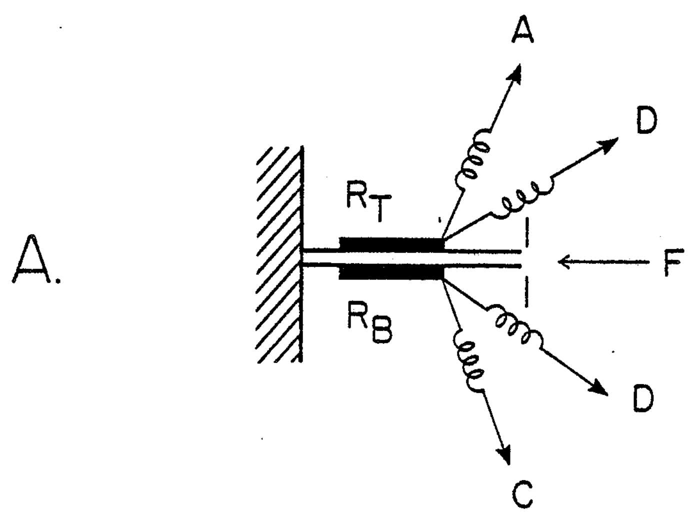
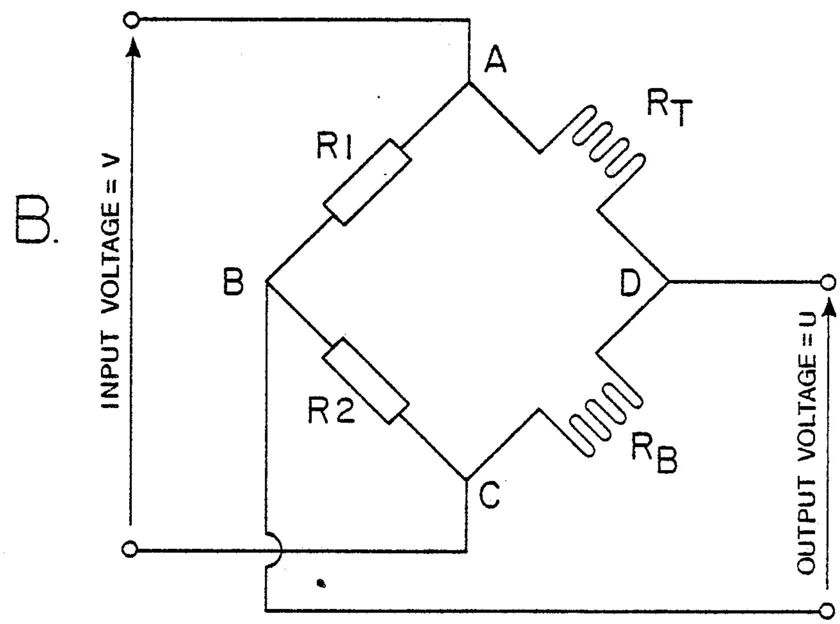


FIGURE 3a. GRAPHIC REPRESENTATION OF A TRANSDUCER



$$U = V_B - V_D$$

$$V_B = V/2$$

Legend

R1, R2 : Unstrained resistances

R_T (top), R_B (bottom): Strain gauges

F - Stainless steel cantilever spring

FIGURE 3b. SCHEMATIC DIAGRAM OF CONSTANT VOLTAGE FOUR-ARM WHEATSTONE BRIDGE

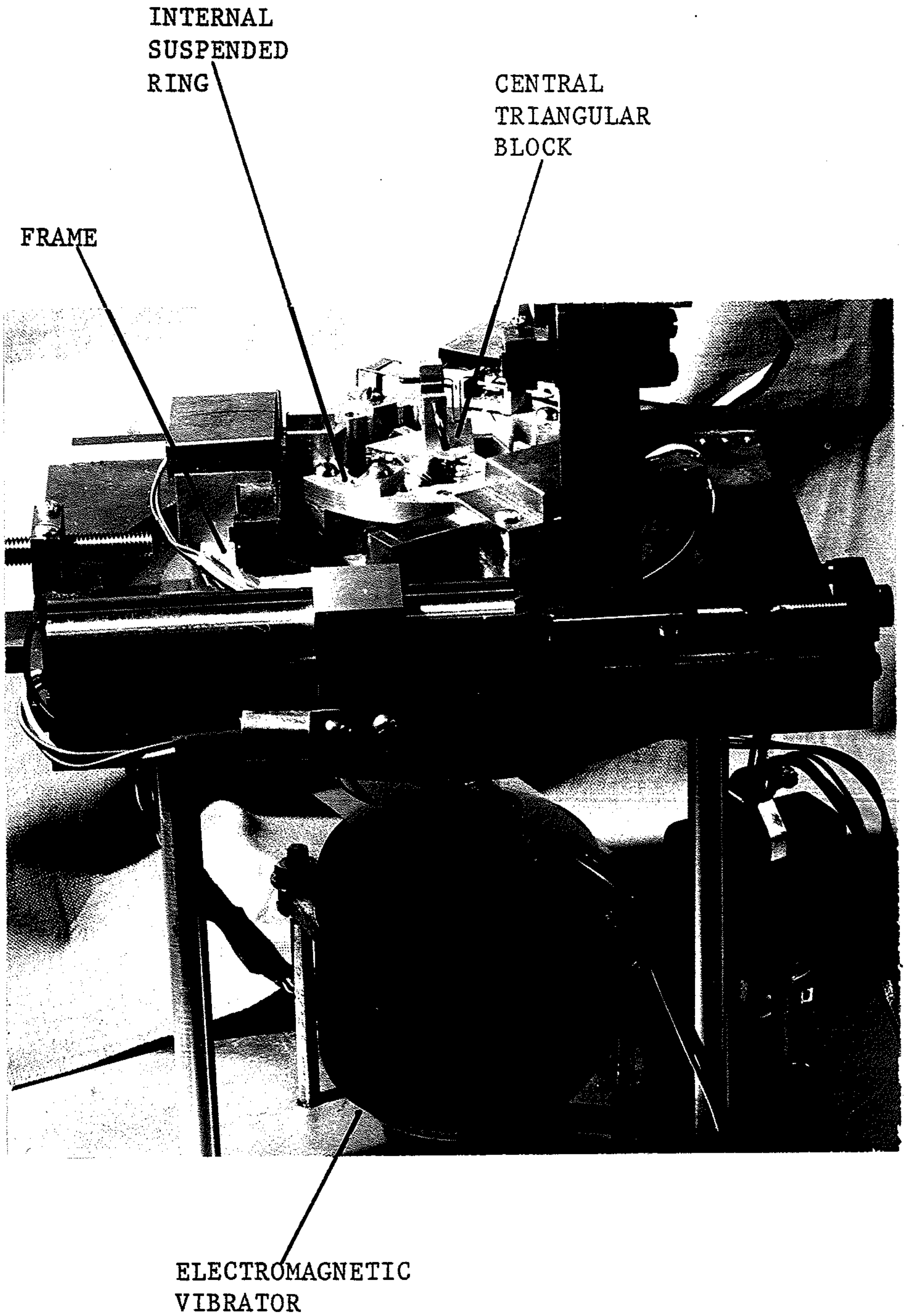


FIGURE 4. GENERAL VIEW OF MEASURING INSTRUMENT

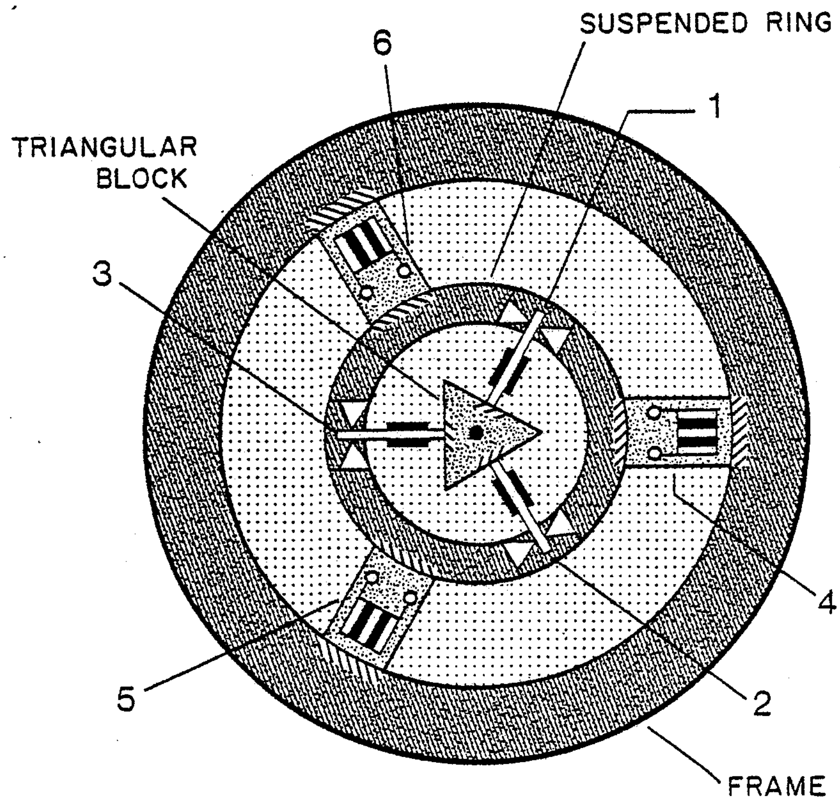
In the instrument, two types of transducers are used, type A and type B as evident in figure 5. The type A transducers (1,2,3) measure the horizontal forces and the pivoting moment. They are rigidily attached to the triangular shaped central block and are free to slide horizontally through their respective contacts located on the suspended ring. The type B transducers (4,5,6) measure the vertical components of force and moments in the horizontal plane. These transducers are rigidly attached on one end to the frame of the instrument and on the other end to the suspended ring.

Modifications to the original design of Paquien by McLachlan (1979), have alleviated the buckling problems reported by Paquien.

The calibration of the measuring instrumentation was initially done by McLachlan (1979). The calibration procedure involved the application of known forces and moments in three dimensions so that appropriate constants could be determined. These constants when multiplied by the recorded strain gauge output ensured that the sensitivity of all gauges were the same, in both a push or pull direction, and relative to each other. The appropriate multiplication constants, also allowed a direct reading of the strain gauge outputs in grams of force and grams-millimeters of moments.

The instrument proved, after the calibration procedure, to have a maximum force range of 130 gm. and a moment range of 2300 gm.-mm., with a random error within plus or minus 3% of full scale.

This accuracy was felt to be more than adequate for the experimental work. A subsequent calibration check, performed as part of



TYPE 'A' TRANSDUCER: 1, 2, 3

TYPE 'B' TRANSDUCER: 4, 5, 6

FIGURE 5. GRAPHIC REPRESENTATION OF INTERNAL STRUCTURE OF MEASURING INSTRUMENT

this investigation, confirmed this accuracy.

DATA AQUISITION SYSTEM (D.A.S.)

The D.A.S. was utilized to measure the electrical outputs of all transducers in the measuring instrument. The D.A.S. possesses a scanner which allows the assessment of each transducer output separately. These values are relayed to the computer to allow the calculation of the forces and moments generated when the measuring instrumentation is loaded.

The control of the D.A.S. scanner is accomplished by the minicomputer. The details of the control program and methods of recording from the transducers are given by Paquien (1978).

MINICOMPUTER

The minicomputer utilized in this investigation was a Hewlett-Packard 9830A interfaced with an X-Y plotter, a printer, a recording system, and the data aquisition system (D.A.S.). The minicomputer was used in both the calculation and collection of data, and also as the controlling element in the experimental routine. The computer is capable of executing the experimental procedure by using an interface system (BUS) which allows a means of communication between instruments involved in the measurement system, and is a way of transfering data between devices.

The use of the computer as a controlling device, provided a continuous check on the instrumentation involved to ensure that it was functioning properly. This feature prevented improper data, due to equipment malfunction from being taken. The minicomputer was responsible for ensuring that all steps necessary to run through an experiment were accomplished before and during the experimental run. It also enabled data to be taken with little danger of human error due to fatigue. Finally, it permitted the transducer outputs to be stored on magnetic tape at the end of each experimental run.

Two computer programs written by McLachlan (1979), were utilized in the investigation. Both programs were written in BASIC, and consisted of a data aquisition program, and a data analysis program.

The data aquisition program was designed not only to collect the data from the strain gauges, but also, as described above, to control and safeguard the data collection.

The flow diagram in figure 6, illustrates the salient features of the data aquisition program.

The second computer program, was designed to provide an analysis of the raw data and, as figure 7 indicates, to plot selected quantities and to calculate the slopes of the selected plots. The program allows the horizontal axis to be proportional to force or to activarion distance, and the vertical axis to moments or forces. The use of slopes in this investigation will be explained in a further section.

The purpose of the plot routine was to provide a visual interpertation of the results. This proved to be important in those situations where the slope values of two curves are similar but the curves had different properties eg. different intercepts with the verical

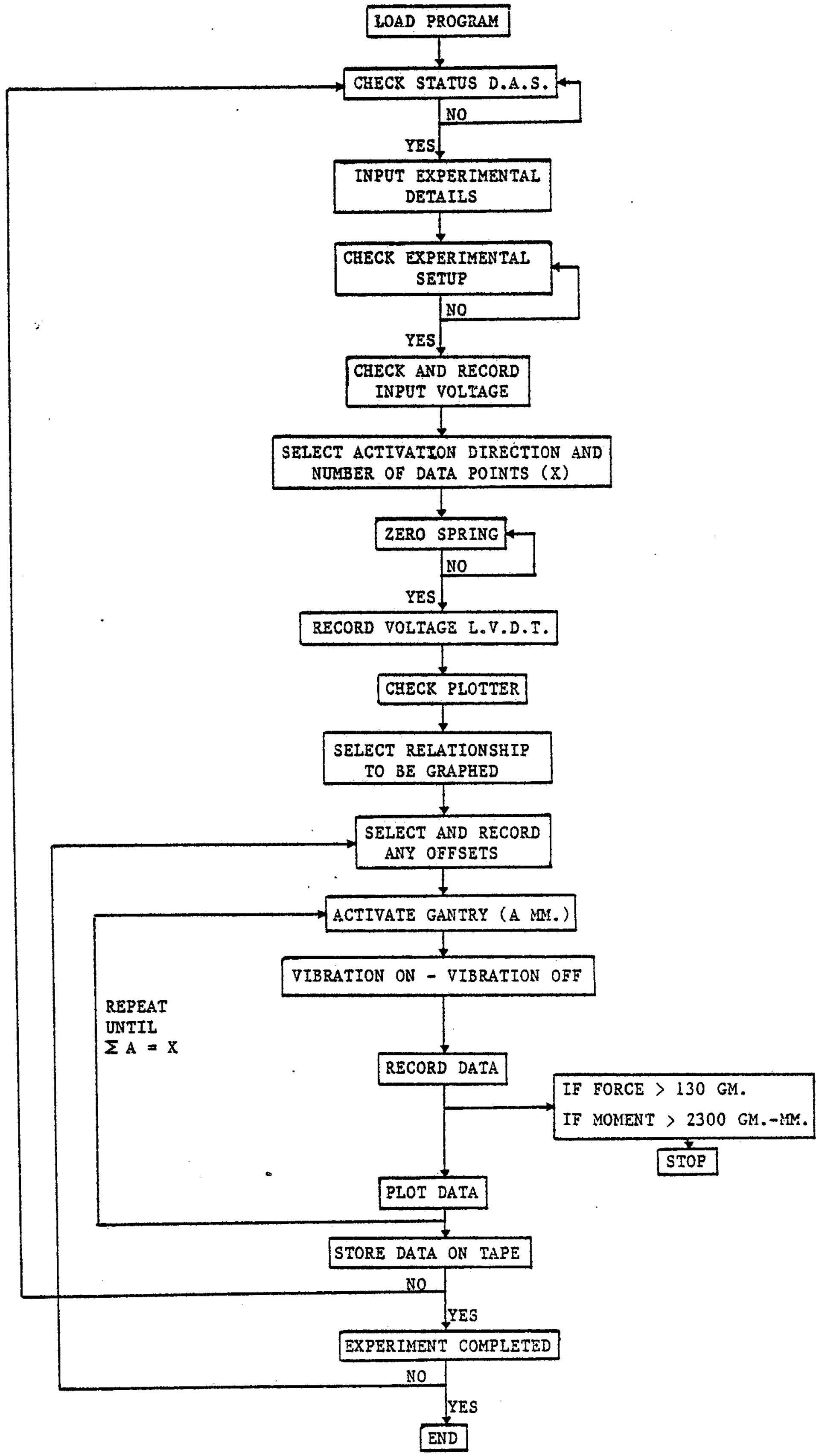


FIGURE 6. FLOW DIAGRAM DATA AQUISITION PROGRAM

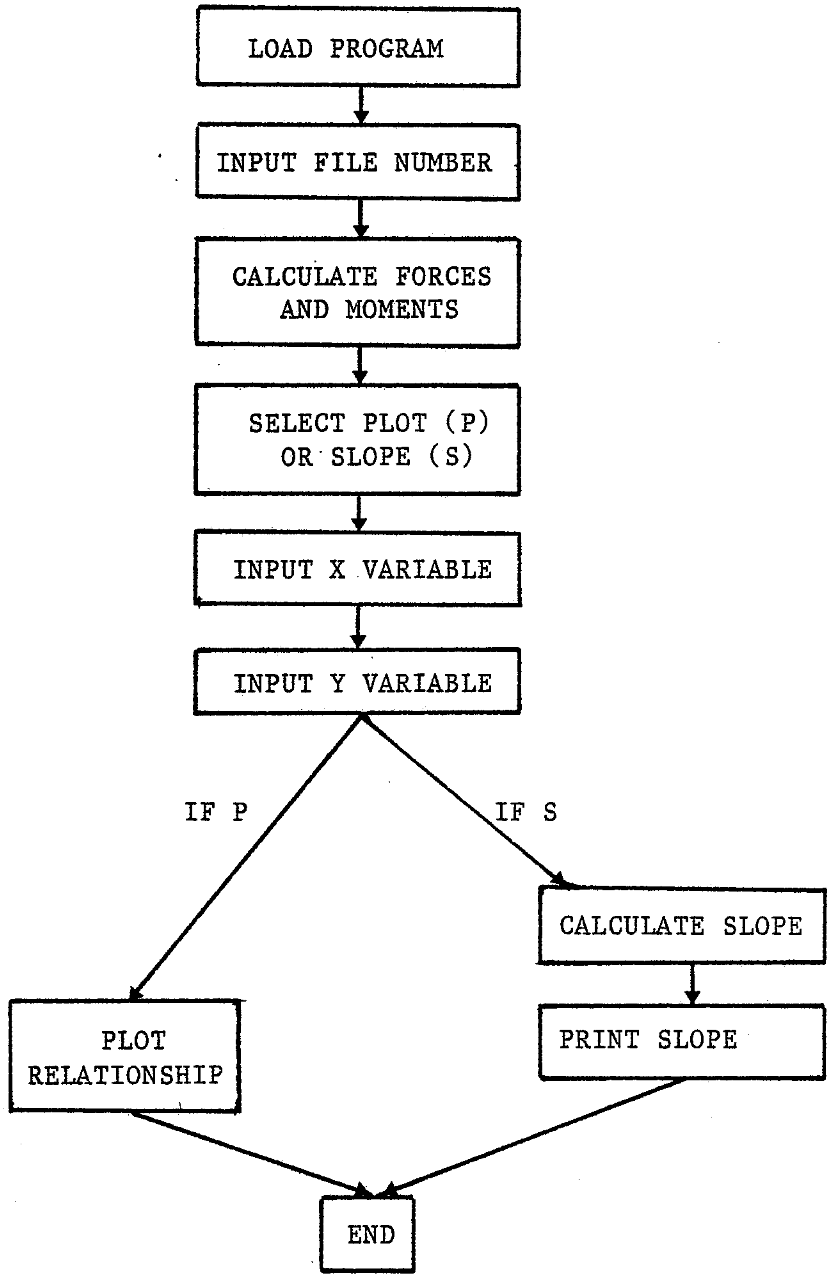


FIGURE 7. FLOW DIAGRAM DATA ANALYSIS PROGRAM

axis.

This program therefore allowed a plotting of the data, and also enabled the large volume of data collect to be substantially reduced to a more manageable size, by the calculation of slope values.

ACTIVATION SYSTEM

In orthodontics it is not uncommon to have a situation where the ends of a retraction loop may not be on the same plane in a horizontal or vertical direction. If the ends of the loop are rigidly attached to the abutment teeth, the net effect of having the ends on different levels will be to introduce unknown forces and moments .

Numerous investigators in the past have studied the effects of activation in a single plane assuming that the ends of the loop were in the same plane. The effects of imperfect alignment of the ends of the loop during activation has not been reported. As a result of this, the activation system (fig. 8) was designed to have the ability to produce activation of a loop in three dimensions. This allowed the investigation of the effects on the force production of not having perfect alignment of the ends of the loop.

In the present investigation, the x direction was the principle direction of activation of all loops. The loop to be tested, was attached between the central triangular block and the vertical activation post, so that when the activation plate was moved the loop became activated. The attachment of the spring to the activation system, was accomplished by clamping the mounting tube on the loop to the

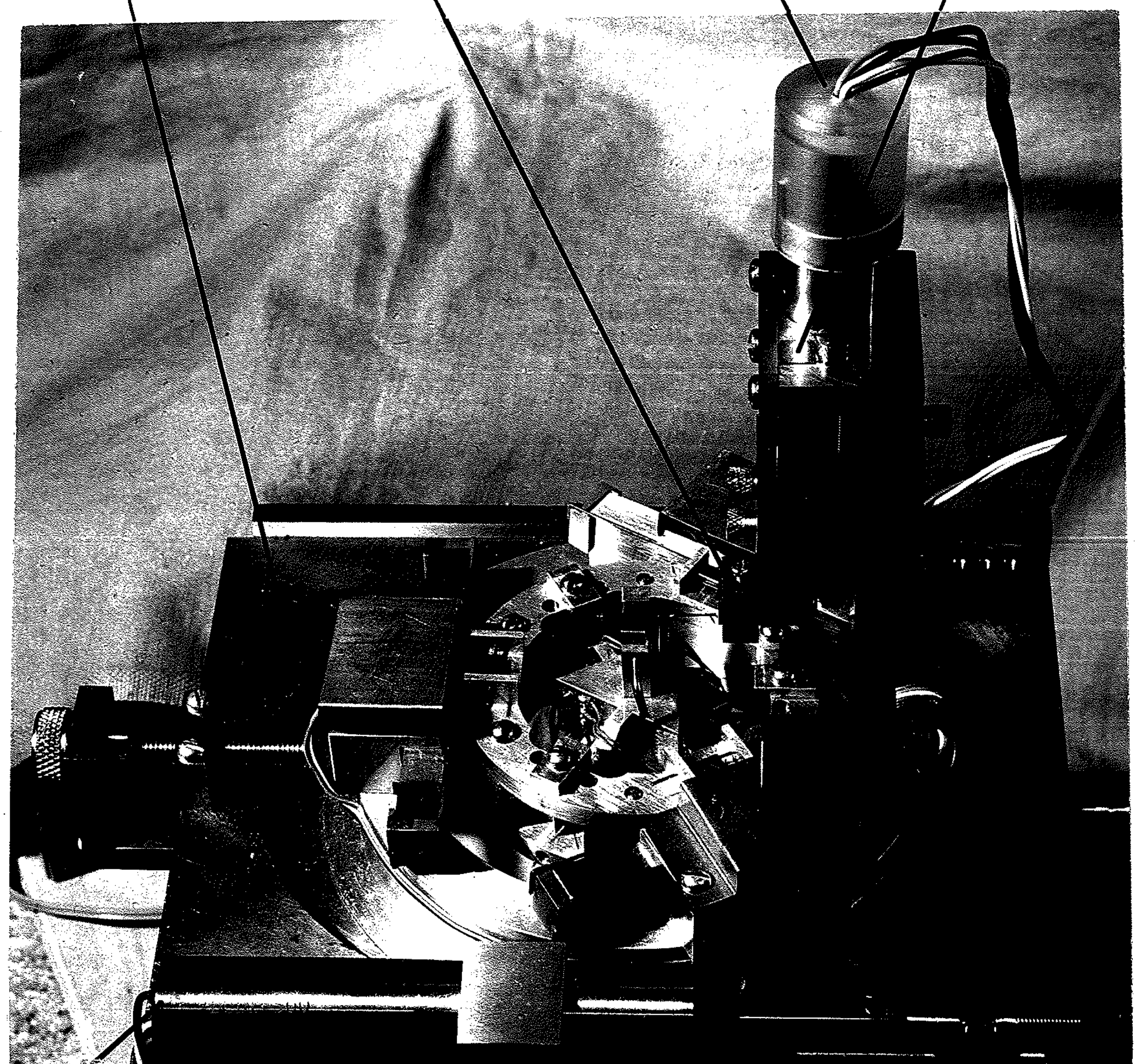


FIGURE 8. ACTIVATION SYSTEM

vertical activation post. Activation in the other planes of space, can also be accomplished by activating the loop in the appropriate direction. The amount of activation in both the x and y direction is monitored by a linear voltage displacement transducer (L.V.D.T.).

The activation system, allowed an activation range of plus or minus 26mm. in a horizontal direction and plus or minus 16mm. in a vertical direction. In this range of values, any amount of activation and any number of activation points could be taken. In most experimental situations, a range of 2mm. in the x direction (mesial-distal) with ten activation points was selected. The amount of activation once selected was controled by the minicomputer.

TOOTH MODEL

The attachment of the loop to be tested to the central triangular block of the measuring instrument, was accomplished using a mechanism which was designed to duplicate the dimensional relationship that exists between a cuspid tooth (with a bracket on the buccal), and a retraction loop. This attachment will be referred to as the model tooth.

The model tooth (fig. 9) is attached at a right angle, to the central triangular block of the measuring instrument. It is constructed of aluminum to reduce its weight and thereby reduce the load placed on the measuring instrument. It is of prime importance that the model tooth be a rigid body and as long as it is rigid, its shape is not important. The shape in figure 9 was utilized more for convenience in construction than for any other reason.

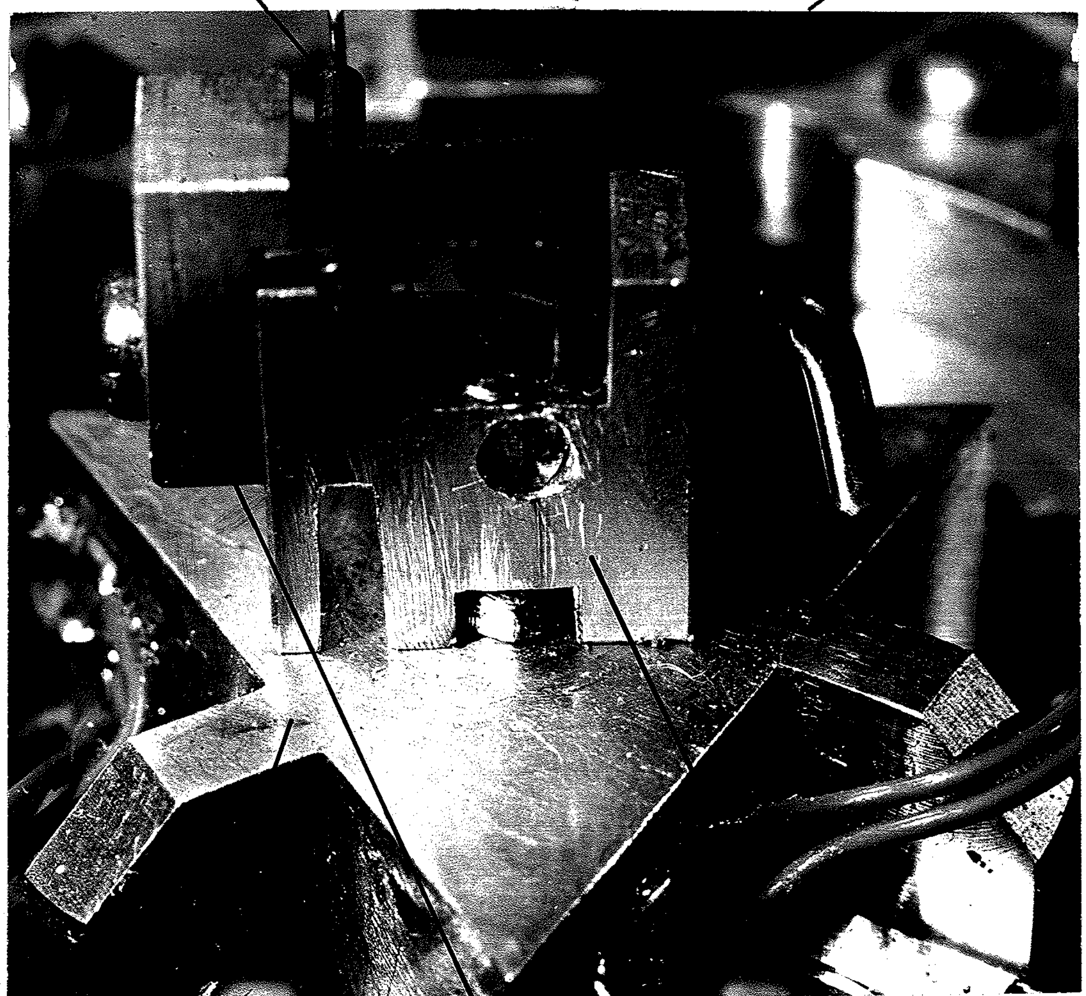


FIGURE 9. MODEL TOOTH

Burstone (1962) has estimated the center of resistance of a cuspid tooth to be .6 times the distance from the gingival margin to the apex. For the purposes of the present investigation, this value was taken as sufficiently accurate. By utilizing average values for cuspid dimension (Wheeler 1974), and assuming that in an orthodontic case the bracket would be placed in the middle 1/3 of the buccal surface of the crown, the following distances from the center of resistance to the bracket on the cuspid were decided upon.

The perpendicular distance from the center of the bracket, to the center of resistance was 12 mm., while the perpendicular distance from the base of the slot in the bracket to the long axis of the tooth was 4.2 mm. These dimensions were utilized in the construction of the model tooth. Figure 10 diagramatically shows the relationship of the cuspid to the model tooth.

The loop to be tested was attached to the model tooth using a clamping mechanism (fig. 9) which was designed to ensure that no undue pressure was applied to the central triangular block when the loop was placed in the measuring instrument.

MOUNTING

A procedure for mounting the loops to the appropriate clamping mechanism was deemed necessary to possess the following characteristics:

(1) it retained the loop in the measuring instrumentation so that no slippage of the end points of the loop occurred as it was loaded,

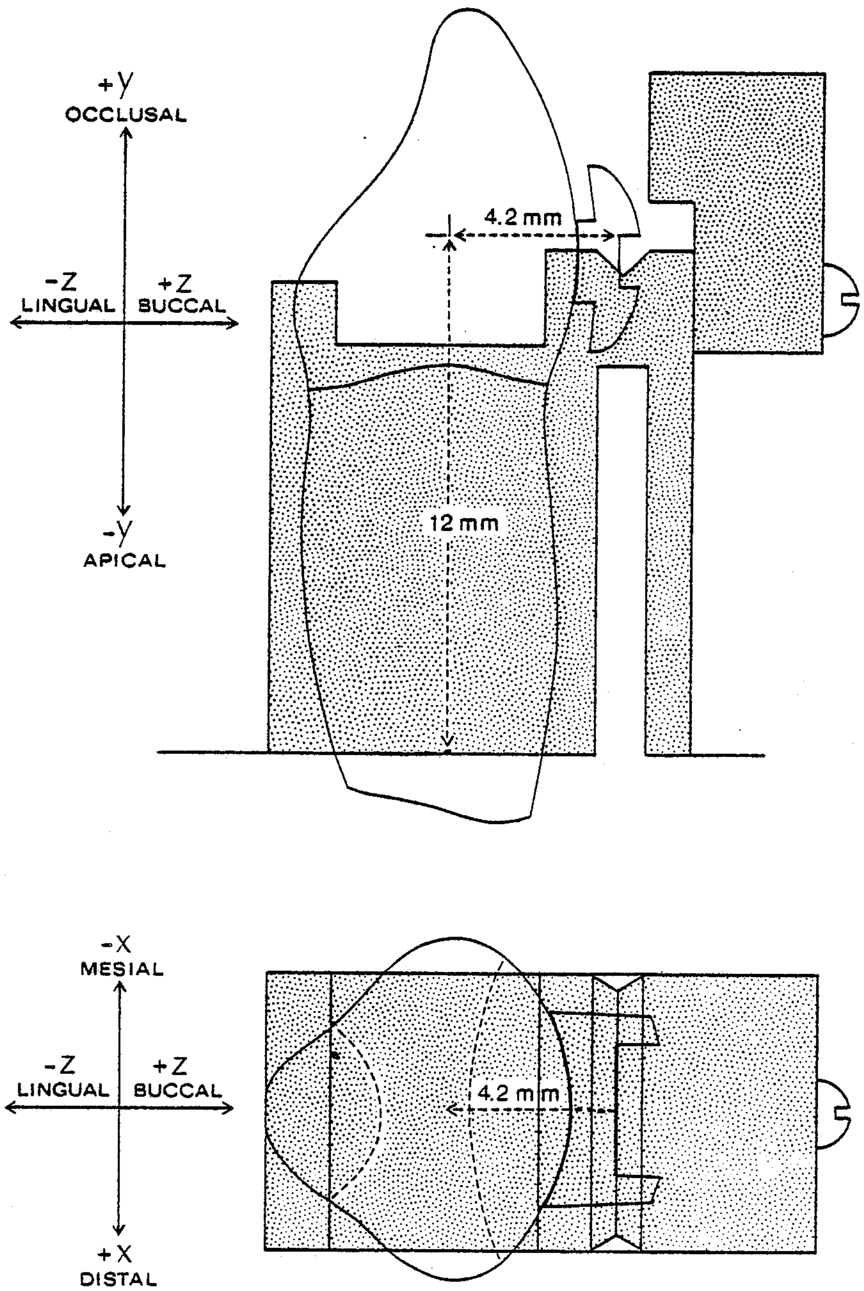


FIGURE 10. RELATIONSHIP OF A BRACKETED CUSPID TO THE MODEL TOOTH

(2) it maintained the ends of the loop in a rigid fashion ie. allowing no movement in a horizontal or vertical direction at the mounting tube-loop interface during loading,

(3) it allowed the freedom of using different diameters of wire (although this was not done in the present investigation) without necessitating the changing or alteration of the testing apparatus,

(4) it allowed a change in the placement of the vertical portion of the loop in a horizontal direction, while still using the same loop, thereby avoiding the error that can arise in the fabrication of loops (Vanderby et al 1977),

(5) it could be applied to either end of the loop and be compatable with the testing apparatus,

(6) it was easy to use and inexpensive.

To the above ends, the following mounting procedure was developed and utilized.

Stainless steel tubing (outside diameter 1.3 mm., inside diameter .7 mm.) was utilized as a common element in the mounting of all loops to be tested. By using a common size of tubing only one attachment mechanism on the measuring instrument was required. The inside diameter would allow wires up to diameter .65 mm. to be tested without alteration of the instrumentation.

The loops examined were mounted to the tubing as illustrated in figure 11.

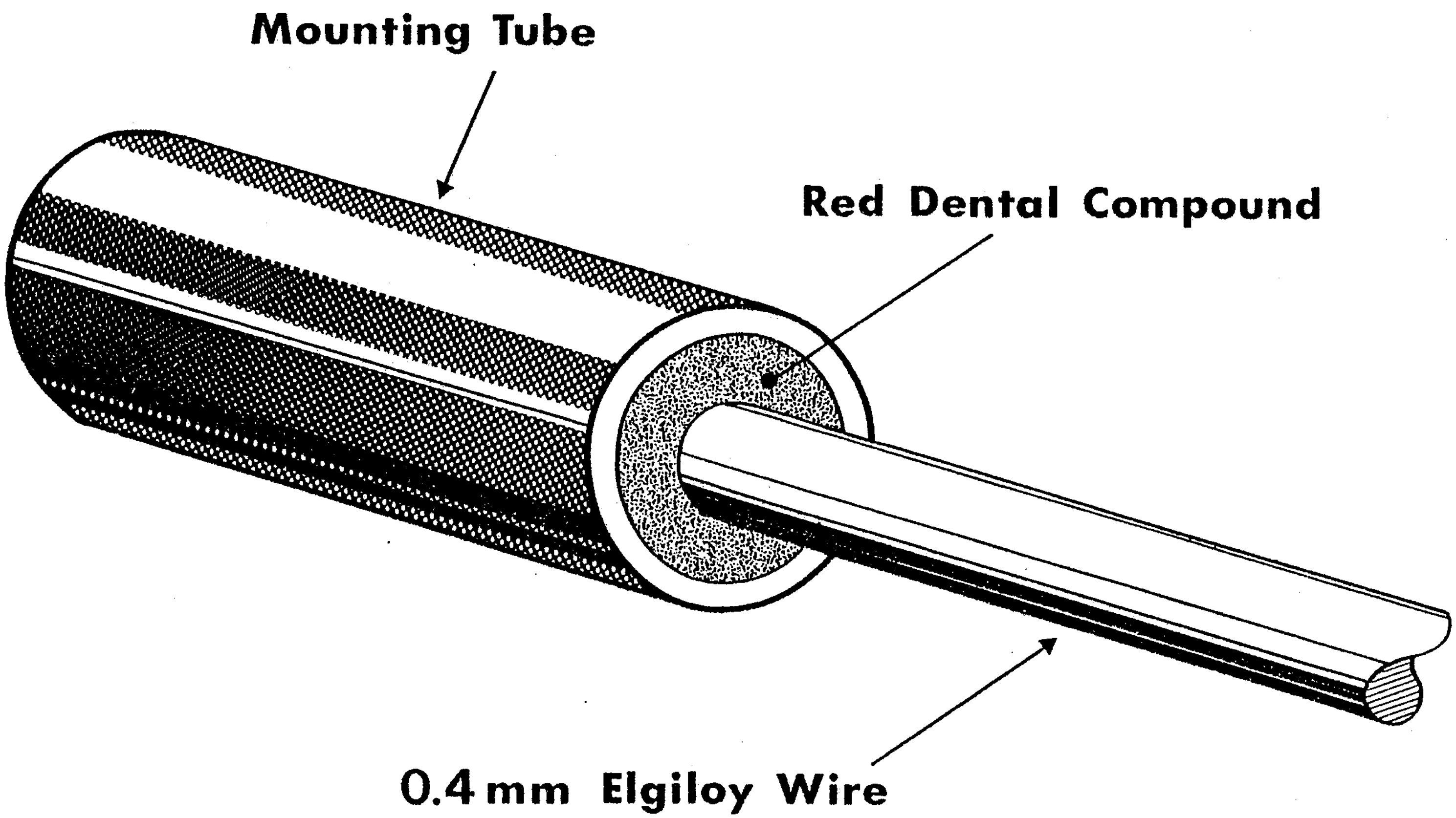


FIGURE 11. GRAPHIC REPRESENTATION OF THE RELATIONSHIP OF THE WIRE TO THE MOUNTING TUBES

To attach the loops to the tubing and also to fill in the space between the wire and the inside walls of the tubing, hot, red dental compound (temperature approximately 50 - 60 degrees C) was injected into the tube once the wire was placed in the correct position ie. centerd in the tubing. The equipment in figure 12 was utilized to accomplish this.

Dental compound was chosen as the cementing medium between the tube and loop for the following reasons:

(1) it is inexpensive and easy to work with,

(2) it sets quickly from a fluid to a solid state,

(3) it has low thermal conductivety (Skinner and Phillips 1967) and therefore little transfer of heat to the wire occurs if the tubing is heated,

(4) the solid compound is rigid with little or no flexibility, so that when the loop is loaded, there will be no distortion of the compound,

(5) the adhesive properties of the compound are such that either the loop is held solidly when it is loaded or there is complete disassociation of the loop from the compound (immediately visible), causing the loop to slide freely,

(6) the compound possess a low melting point ie. it achieves approximately 95% of its flow at a temperature of 50 degrees C (Skinner and Phillips 1967), a temperature which will not effect the properties of the wire.

The loop to be tested was attached with tubes at both ends, with

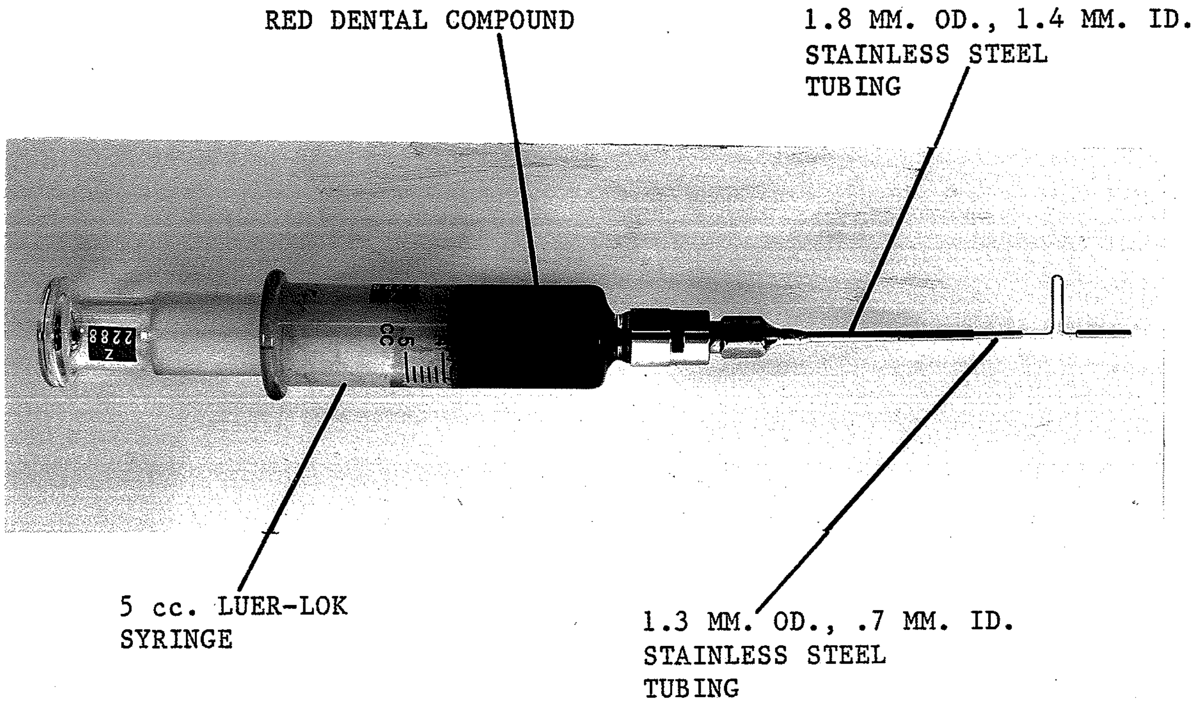


FIGURE 12. EQUIPMENT USED FOR ATTATCHING MOUNTING TUBES TO THE WIRE LOOPS

the distance between the tubes 12mm. By gently heating the tubing, the compound in the inside of the tube becomes fluid enough to allow the wire to slide freely, thereby allowing the changing of position of the vertical portion of the loop within the 12 mm. distance.

In all the experimental procedures, the distance between the mounting tubes or the "interbracket distance" was taken as 12 mm. This measurement assumes that the loop begins at the end of the tube. This assumption is only valid if the compound is flush with the end of the tube. When the compound is not flush with the ends of the tube, the loop is in fact longer. In figure 13, position A, the loop's origin is at M while in figure 13, position B, the origin is at L such that the loop is in fact L-M mm. longer.

By heating the compound and sliding the loop in the tube, it is possible to produce a situation as is pictured in figure 13, position B, due to the adhesiveness and fluidity of the softened compound.

In order to assess the accuracy of the method of mounting and to evaluate any error associated with moving the wire in the tubing, a preliminary investigation was carried out.

This investigation involved a cantilever spring made of .016in. diameter stainless steel orthodontic wire mounted in a tube using the method dsecribed. This cantilever spring - mounting tube combination is a replica of the experimental situation as far as the mounting procedure is concerned. The spring was loaded with three known weights, applying them one at a time until a total of three weights were added. The loads used were comparable to those obtained in tests

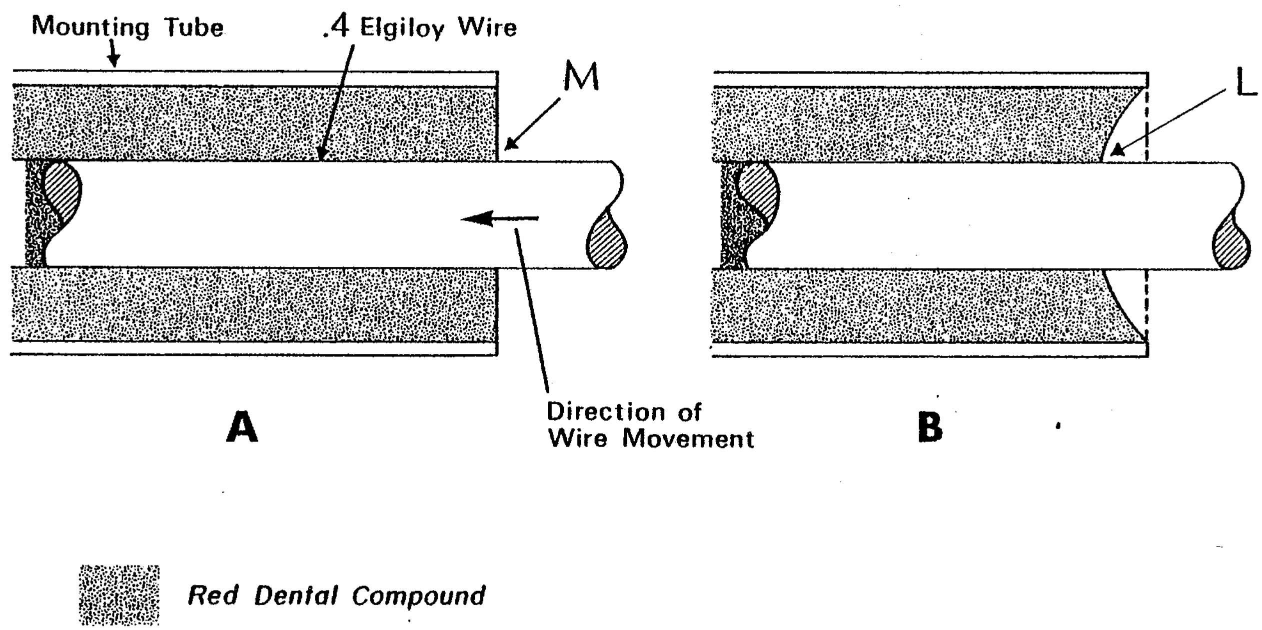


FIGURE 13. GRAPHIC REPRESENTATION OF THE EFFECT OF MOVING THE WIRE IN THE MOUNTING TUBE

on appliances. The deflection of the cantilever after each weight addition was measured using a micrometer gauge, accurate to .01 mm.

The length from the end of the tube to the point of application of the load was initially 12 mm. By heating the tube as described above, the length of the spring was decreased 1 mm. and the above procedure was carried out for lengths of 12, 11, 10, 9, 8, 7, and 6 mm.

The procedure was repeated three times for each length using the same weights in a random order. The mean deflection for each weight addition was calculated and plotted as a load-deflection curve for that length. The slope of the load-deflection curve was then calculated and plotted against the cube root of the length of the cantilvever spring. This line was then extrapolated back to the x axis to assess where the origin (in relation to the mounting tube) of the loop was.

The results indicated that a total error of .2 mm. occured if the wire was moved a total distance of 6 mm. through the tubing. Since in the actual experimental procedures the wire would not be moved this amount, the error determined above was considered acceptable.

An investigation into the strength of the mounting procedure was not undertaken as the retention of the loop in its mounting tube would be an "all or nothing" situation. This arises from the brittle nature of dental compound at room temperature.

ACCURACY AND CALIBRATION CHECK

An investigation of the modified instrumentation of Paquien was undertaken to assess the random error in the apparatus and also to assess the accuracy of the measuring instrument.

The complete details and results of the investigation are available in the appendix. The investigation was performed in two segments. The first was designed to assess the random error and consisted of repeated activation of a coiled spring in the x direction (2.5 mm.). Ten data points were taken at the same amount of activation (eg. .25 mm., .50 mm., etc.) with the complete activation of the spring repeated ten times. The means and standard deviation of each point of activation for all forces and moments were calculated.

The second segment of the investigation consisted of comparing the measured values of forces and moments to the calculated forces and moments of the spring. The spring was separately calibrated using dead weights.

The results revealed that the random error for the instrumentation was less than plus or minus 1% of the total range for both forces and moments. The instrumentation also possessed an accuracy such that the measured values for forces and moments were within plus or minus 3% of the calculated force and moment values.

This degree of accuracy and reproductability was deemed entirely acceptable for the experimental investigation of orthodontic appliances.

DESCRIPTION OF LOOPS TESTED

Six cuspid retraction mechanisms were utilized in the present study. They were selected to be representative of the types of mechanisms that are utilized by orthodontists for the retraction of cuspids and include the following designs:

(1) a vertical loop which when activated, led to an opening of the loop's inside diameter ie. the inside diameter increases, (fig. 14a - open vertical loop),

(2) a vertical loop which when activated led to a reduction of the inside diameter of the loop, (fig. 14b - closed vertical loop),

(3) a vertical loop with a one and one half turn helix at its apex which when activated, produced an increase in the inside diameter of the loop, (fig. 15a - open vertical loop with a 1 1/2 turn helix),

(4) a vertical loop with a one and one half turn helix at its apex which when activated, produced a decrease in the inside diameter of the loop, (fig. 15b - closed vertical loop with a 1 1/2 turn helix),

(5) an L shaped retraction loop, which when activated, produced an increase in the inside dimensions of the loop, (fig. 16a - an open L-loop),

(7) a Burstone* type E cuspid retraction assembly, (fig. 16b).

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* Ormco, Glendora, California.

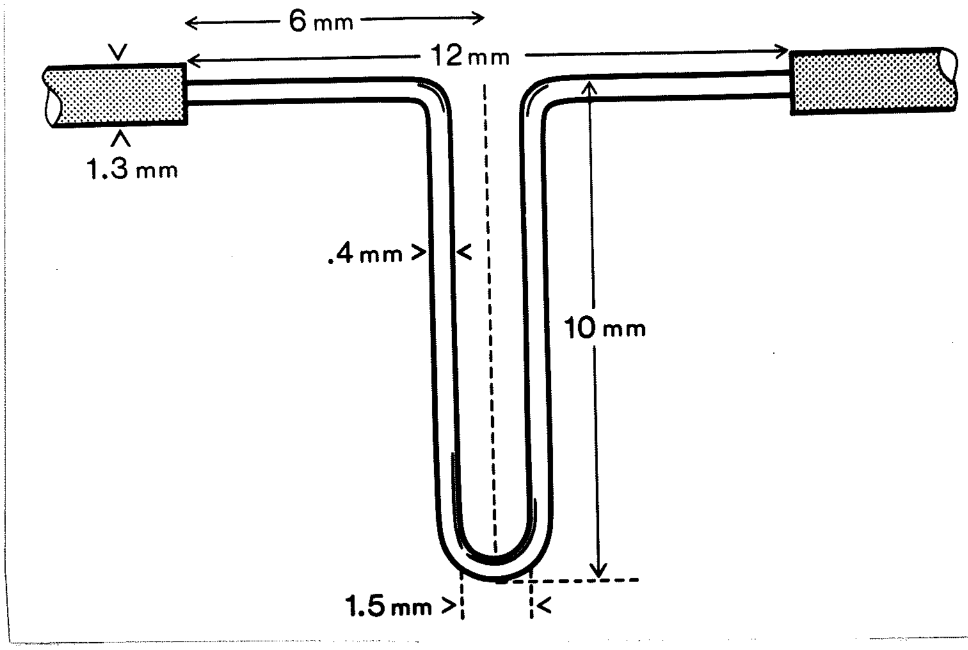

FIGURE 14a. OPEN VERTICAL LOOP

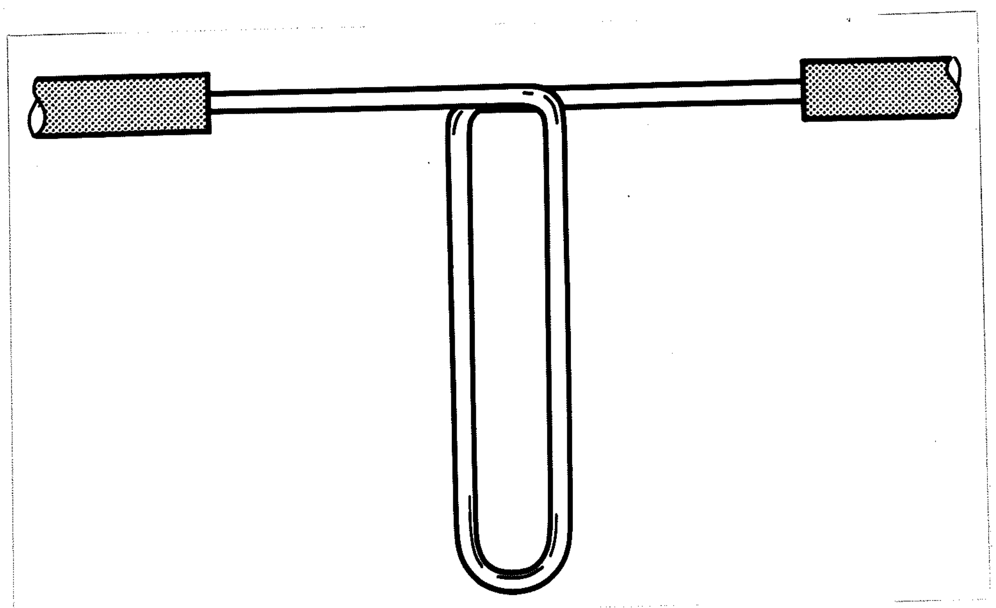

FIGURE 14b. CLOSED VERTICAL LOOP (SAME DIMENSIONS AS IN 14a)

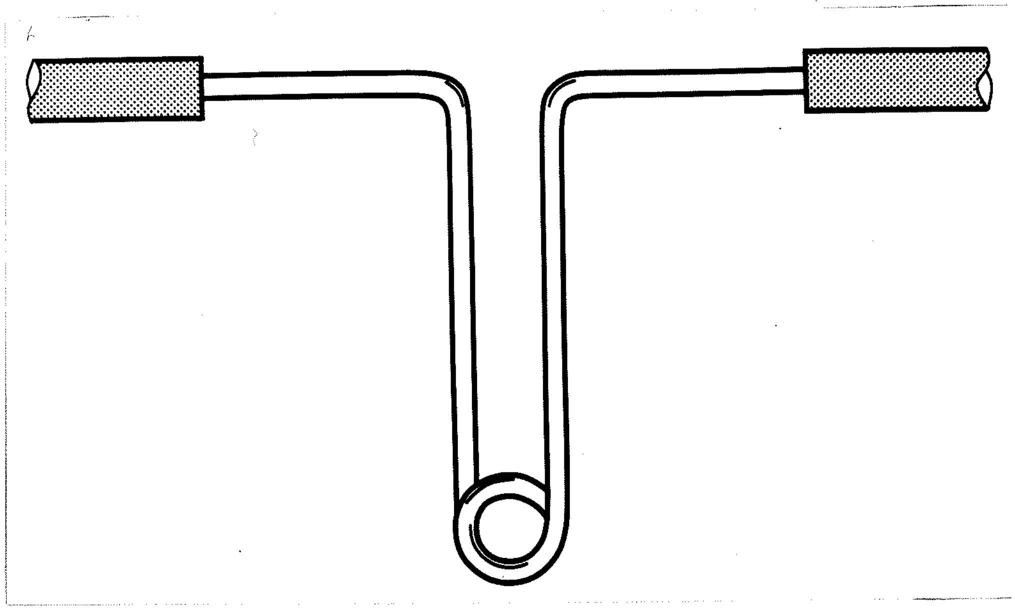

FIGURE 15a. OPEN VERTICAL LOOP WITH A 1 1/2 TURN HELIX (SAME DIMENSIONS AS IN 14a)

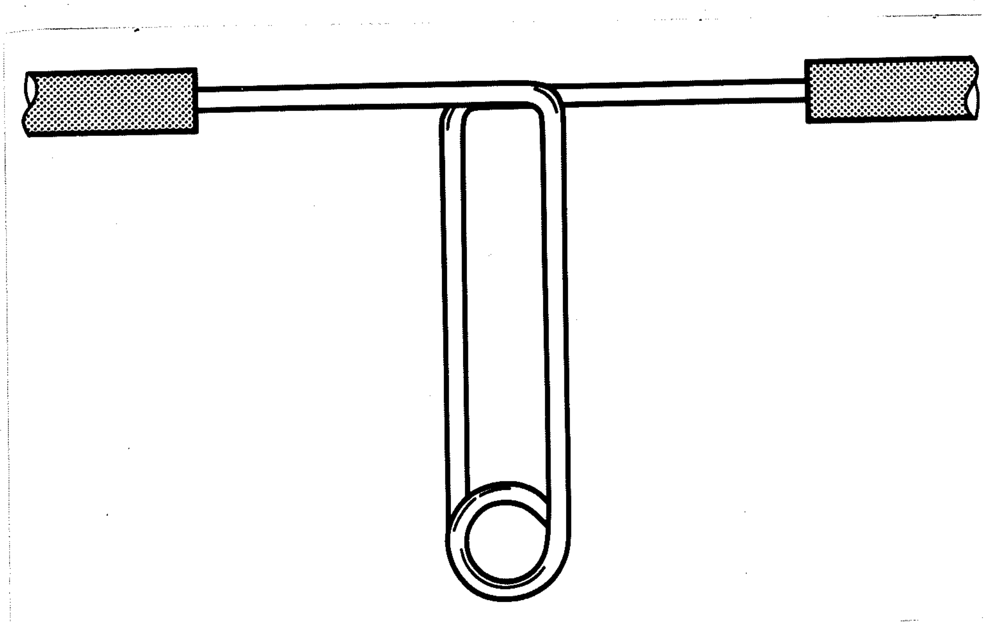

FIGURE 15b CLOSED VERTICAL LOOP WITH A 1 1/2 TURN HELIX (SAME DIMENSIONS AS IN 14a)

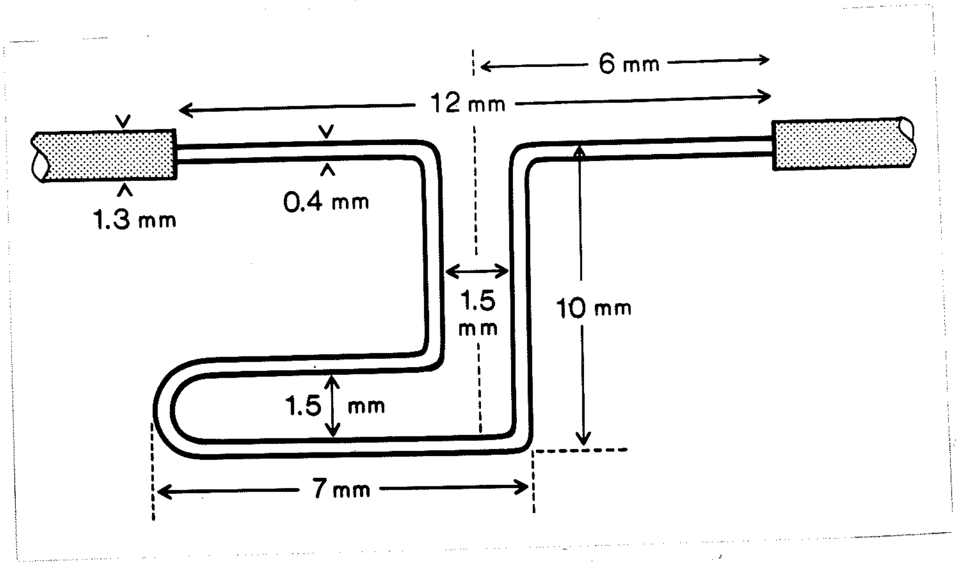

FIGURE 16a. L-LOOP

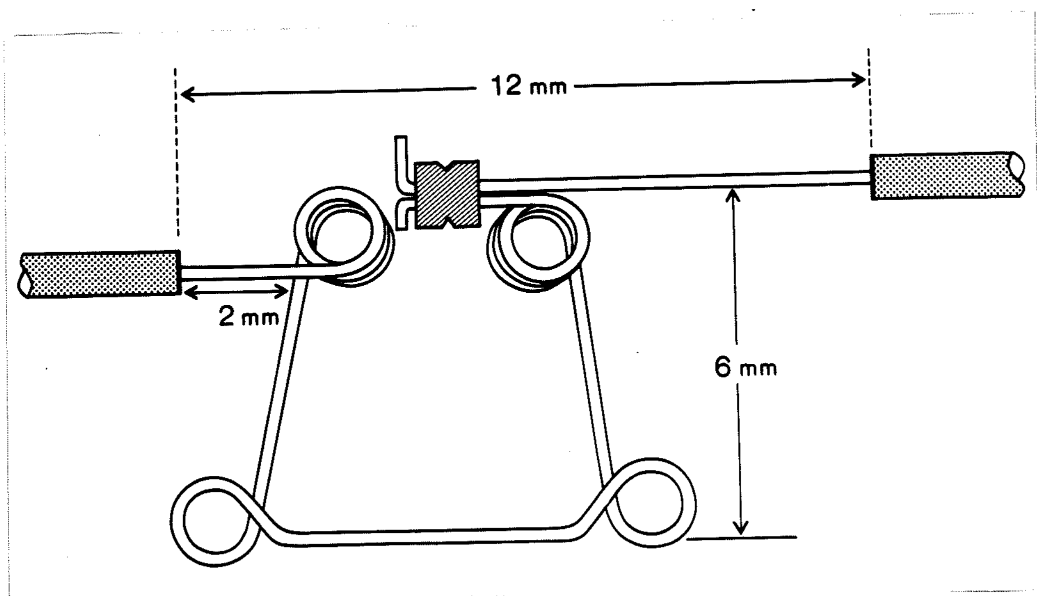

FIGURE 16b. BURSTONE LOOP

All the retraction mechanisms (except the Burstone retraction assembly), were made by the author from the same batch of .016 inch diameter yellow Elgiloy#. Yellow Elgiloy was selected for ease of fabrication.

The Burstone retraction device was tested as produced by its manufacturer and was composed of .010 x .020 in. stainless steel with an .017 x .025 in. stainless steel arch segment.

All retraction assemblies were tested in an unheat-treated state.

All vertical loops produced by the author, ie. loops 1, 2, 3, 4, and 5, possessed a vertical height of 10 mm. and an inside diameter (distance between the vertical legs of the loop) of 1.5 mm. at the base of the loop. A 10 mm. height was chosen to allow a larger deflection of the loop without overloading the force limits of the testing instrument.

The L-loop was also 10 mm. high, but with a 7 mm. horizontal extension at its apex. The inside diameter of this loop was also 1.5 mm.

The Burstone loop as tested was 6 mm. high.

The horizontal length of all loops tested was 12 mm. This distance was measured from the inside edge of one mounting tube to the inside edge of the opposite tube (fig. 14a).

Due to the extreme variability that arises due to the manufacture

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#Rocky Mountain, Denver, Colorado.

of orthodontic devices (Vanderby et al 1977) even with the use of a bending jig, only one loop of each design was used to be representative of that particular design. By eliminating the above variability and utilizing the same loop in various investigations it was felt that the properties of the loop, due to its design could be examined more accurately.

All loops except the Burstone were bent to a template, and were made to lie flat on it. Care was taken not to overbend the loop during construction. If repeated bending of parts of the loop was required to get it to fit the template, the loop was discarded and a new one made. This was done to prevent weakening of the wire in those areas where bends were placed, which might effect the properties of the wire at those points.

EXPERIMENTAL PROCEDURE

All experimental procedures involved the same type of activation although the conditions under which the loops were tested was varied. The loops were attached to the activation gantry with the vertical portion of the loop facing towards the central triangular block. The activation gantry prior to this had been moved to its maximum point of activation in a horizontal direction.

The inside end of the mounting tube was placed so that it was flush with the end of the horizontal clamping arm of the gantry. The clamp around the arm was then tightened making sure that the vertical portion of the loop was parallel to the long axis of the model tooth. The activation gantry was then adjusted in both a horizontal and vertical direction until the other mounting tube was directly above the slot in the model tooth with the inside of the mounting tube flush with the edge of the model tooth. When this was done, the loop was lowered by adjusting the vertical arm of the activation system until the mounting tube lay passively in the slot on the model tooth. The tube was then clamped to the model tooth. The above procedure ensured that the loop to be tested was in a completely passive state prior to its being tested, thereby preventing any preliminary force from acting on the measuring instrumentation.

Once the loop was mounted to the measuring instrument (figure 17), a visual check was made to ensure that the vertical portion of the loop was parallel to the long axis of the model tooth and that the horizontal portion of the loop was at right angles to the long axis of the model tooth.

The program for the data aquisition was then run, with a preliminary activation of the loop to be tested, to check on the instrumentation and the loop.

Once the preliminary run was carried out, the activation system in a horizontal direction was set back to the initial zero position (using the L.V.D.T. readouts). The end of the loop attached to the model tooth was then unclamped and the activation system was readjusted as described above so that the loop was in a completely passive position over the slot of the tooth. The loop was then reclamped to the model tooth, ensuring that no undue force was acting on the model tooth.

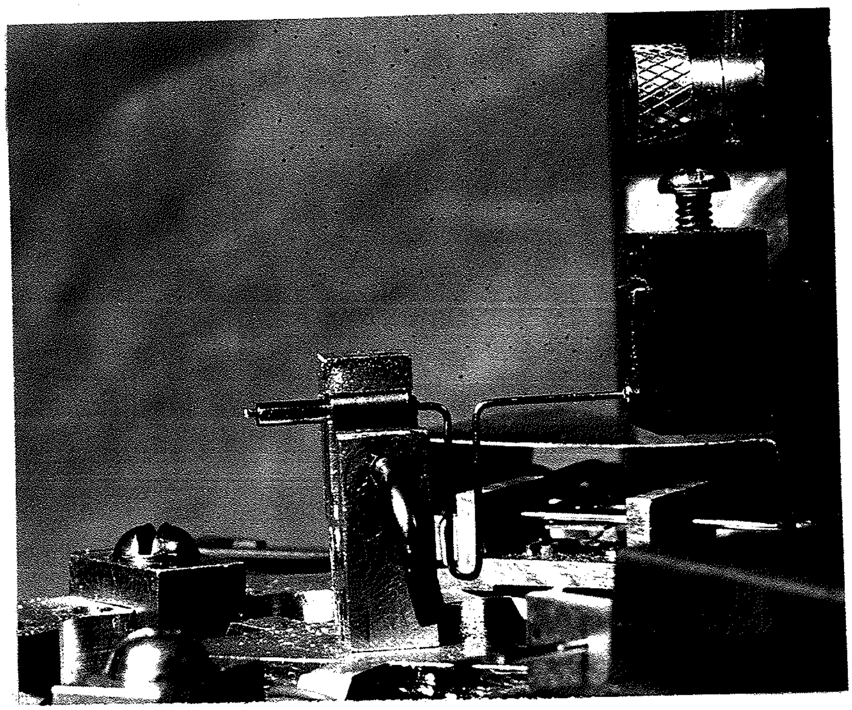


FIGURE 17. OPEN VERTICAL LOOP ATTACHED TO MEASURING INSTRUMENT

This preliminary activation served two main purposes. It allowed, as stated above, a check to be made on the performance of the loop and the measuring instrument. It also took the loop to be tested through its maximum range of activation, thereby checking on any non-linearity of the loop or of the fixing mechanism.

After the preliminary activation was completed, the experiment to be undertaken was run. There were five main experimental procedures undertaken. All experimental procedures were not undertaken at the same time, but attempts were made to carry out each testing procedure under the same temperature conditions ie. 70 degrees F.

The first experimental block consisted of activating the loops, with the vertical portion of the loop centerd between the end points so that the distance from each end point to the center of the vertical portion of the loop was 6 mm. (fig. 14a). This distance was maintained for all vertical loops except for the Burstone which was activated using the dimensions pictured in figure 16b. The activation for all loops, except the Burstone, was 2 mm. with ten activation points taken within that range. Activation for the Burstone was 5 mm. with ten activation points. The experimental routine was carried out using the minicomputer with a zero mm. offset in the y direction. Force in the x direction (since this was the principal component of force) versus activation distance was plotted to check that the experiment was proceeding satisfactorily. When the activation run was completed, the data for each run was stored on magnetic tape.

After each loop was tested, the activation system was returned to zero, as indicated by the LVDT output, before the loop was removed.

This was done to remove any activation in the loop, so that if forces were placed on the loop during removal they would be small and not damage it. During removal the end attached to the activation gantry was removed first to ensure that the loop was completely passive during the unclamping from the model tooth. Each loop was tested individually and the above procedure was carried out in each experiment.

In the second block of experiments, the vertical portion of all loops (except the Burstone) were moved from their central position between the mounting tubes to a new position 1.5 mm. from the model tooth (fig. 18). A 12 mm. distance was still maintained between the mounting tubes. The movement of the vertical position of the loops between the mounting tubes was accomplished utilizing the heating technique described. The Burstone loop was tested as illustrated in figure 16b .

The testing of the loops in this block was done according to the procedures described in the first experimental block.

The results of this block could therefore be compared to the results from the first experimental block, since the only difference between the two situations is the position of the vertical component of the loop.

The third experimental block utilized the same loop arrangements as in block two. In this block though, a variation in the y offset from +1 mm. to -1 mm. taking .5 mm. increments was done. This was done to examine how mis-alignment in the vertical plane affected the performance of the loops. The variation in offset was only examined

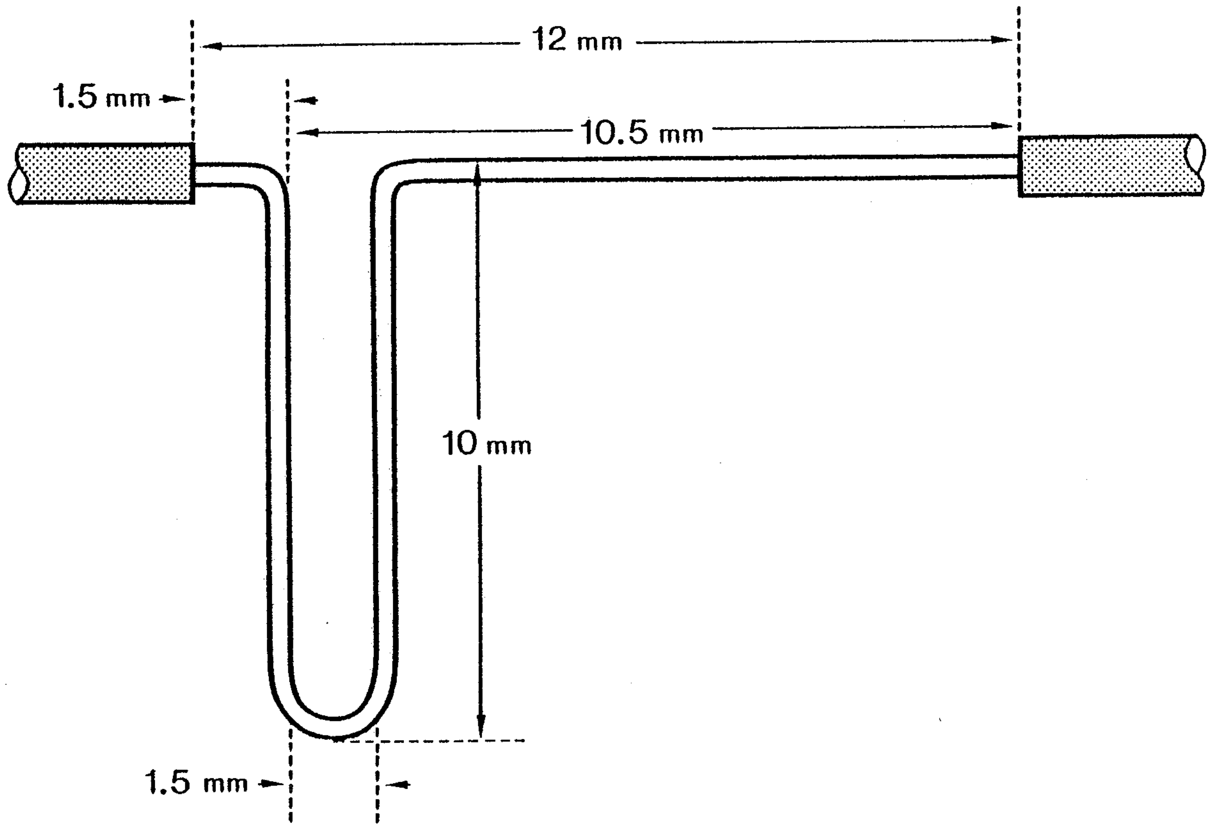


FIGURE 18. RELATIONSHIP OF THE VERTICAL PORTION OF THE LOOP TO THE MOUNTING TUBES IN BLOCK TWO

in the vertical plane ie. along the y axis. Only vertical offsets were examined due to the fact as Waters (1976) points out "that the flexibility for horiztonal displacement of vertical loops is invariably greater than for deflection in the vertical plane." Due to this, it was felt that an examination of the effects of offsets in the extreme would be more significant than looking at less severe effects.

Each loop to be tested was attached to the measuring device as in the previous blocks. The preliminary activation run in this block was done with a +1 mm. y offset. The +1 mm. y offset by preliminary investigation was found to have produced the highest force values during activation and was therefore utilized. At the completion of this run, the y offset was readjusted to zero as was the x activation.

The loop was then unclamped as in the first block, adjusted to a new passive position, and reclamped to the model tooth.

The experimental run began with a -1 mm. y offset with the same x activation as in block two. When this was completed, the x activation was adjusted back to zero, and the y offset was moived .5mm. in a positve direction ie. from -1mm. to -.5mm.. The spring was then reactivated in the x direction as above. This procedure was repeated until a +1mm. offset (five times) in the y direction was reached.

All six loops were tested separately as above producing a total of thirty separate experiments.

The initial examination of the results from the first two experimental blocks revealed that as a result of the activation of the loops, numerous undersirable forces and moments are exerted on the center of resistance of the measuring instrument. In an effort to reduce these deleterious effects, appropriate counter-moments were incorporated into the open vertical loop, and the Burstone loop, and were tested to investigate their effects.

Counter-moments to prevent tipping were examined in the fourth experimental block. The counter-moments were produced by the incorporation of a 30 degree gable bend into the short horizontal arm of the open vertical loop. Gable bends larger than 30 degrees were not examined due to the difficulty of placing the loop into the testing apparatus with larger preactivations. The Burstone loop, on the other hand, was preactivated according to Remise (1978) with 90 degrees of anti-tip moment.

In order to assess the force production of the gable bend, a zero reading of the measuring instrument was taken with the loop in place, but with no gable bend. The loop was then removed and the 30 degree anti-tip gable bend incorporated. The loop was then placed back in the measuring instrument, and a reading (with zero x activation) of the forces and moments generated was taken. The activation in the x direction was then increased as in the first experimental block. After the data collected was stored on tape, the x activation was adjusted to zero and the loop removed.

The Burstone loop with its preactivation, was also tested as above.

At the completion of this experimental block, the loops were adjusted to their original shape using the fabrication templates.

The fifth experimental block involved the placement of anti-rotation gable bends. The gable bends were again placed in the short horizontal arm of the loop. A gable bend of 30 degrees was examined, following the procedure as for the fourth experimental block. The Burstone was again activated according to Remise (1978) with 180 degrees of anti-rotation preactivation.

The combined effects of both anti-tip and anti-rotation countermoments in a loop were not examined due to the difficulty of placement of the loop into the measuring instrument.

Table I provides a summary of all the experimental investigations undertaken.

DATA ANALYSIS

The investigation of orthodontic appliances in three dimensions, resulted in the production of large quantities of numerical data which had to be dealt with. The collection and analysis of the data was simplified by the use of the minicomputer. The analysis of the data however depended on the development of a method which would reduce the data to a workable size, without losing any of the significant information.

All data as collected was stored on magnetic computer tape. The data collected was the electrical outputs of the various transducers. The initial reduction in the data came in the computer programs. By utilizing the methodology described by Paquien (1978), the conversion of the electrical outputs to the forces and moments acting on the cen-

TABLE I

SUMMARY OF EXPERIMENTAL INVESTIGATIONS.

EXPERIMENTAL BLOCK	VERTICAL LOOP PLACEMENT	X ACTIVATION	Y ACTIVATION	ANTI-TIP	ANTI-ROTATION
1	CENTERED	2 MM.	0	0	0
	BURSTONE AS IN FIG. 16B	5 MM.	0	0	0
2	1.5 FROM MODEL TOOTH	AS IN 1	0	0	0
	BURSTONE AS I IN FIG. 16B	AS IN 1	0	0	0
3	AS IN 2	AS IN 1	-1 MM. -.5 MM. 0 MM. +.5 MM. +1 MM.	0	0
4	AS IN 2	AS IN 1	0	VERTICAL LOOP 30 DEG. BURSTONE 90 DEG.	0
5	AS IN 2	AS IN 1	0	0	VERTICAL LOOP 30 DEG. BURSTONE 180 DEG.

ter of resistance of the measuring instrument was possible.

The graphs of the forces and moments plotted during the data collection, revealed the existence of linear relationships.

The equation of a straight line may be written in the form

$$V = a + bH.$$

Any point (H,V) on this line has an H co-ordinate or abcissa, and a V co-ordinate or ordinate whose values satisfy this equation. When H = 0, V = a so that a is the point where the line crosses the V axis, that is a is the V intercept.

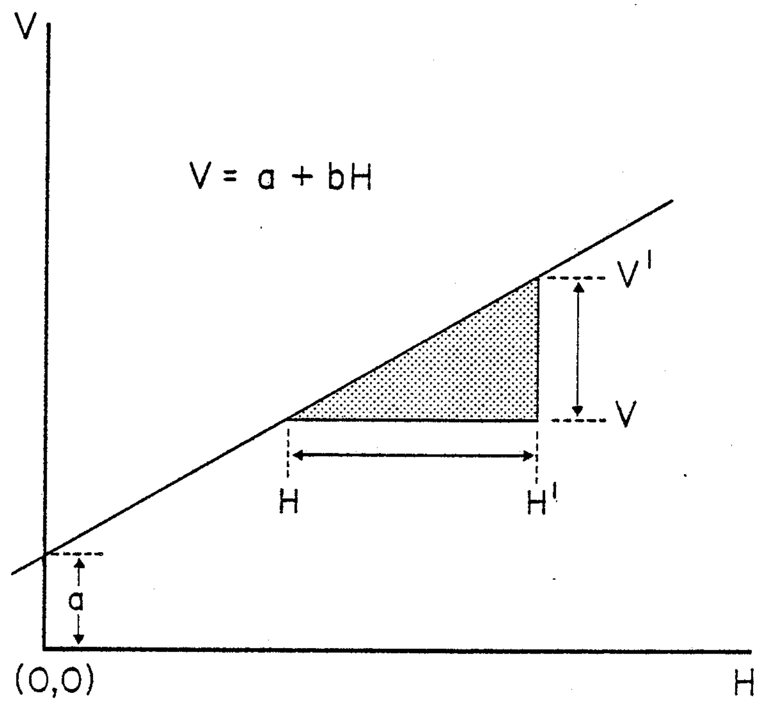
When a = 0 the line goes through the origin. The slope value for the line is expressed by the formula:

$$b = (V' - V)/(H' - H) \quad \text{(fig. 19)}$$

When b is positive, both variables increase or decrease together. When b is negative, one variable increases as the other decreases. For a straight line relationship therefore, the slope and the V intercept uniquely determine and describe the line.

By utilizing the above information, the data was further reduced to the point that two numbers were descriptive of the particular relationship in question, and negated the necessity of dealing with the large volume of absolute data.

The data analysis program (described in the section on the minicomputer) was utilized to calculate the slope for any particular relationship. The calculation of the slope, involved calculating the slopes between successive activation points and then averaging these



$$b = \frac{V' - V}{H' - H}$$

a = V intercept

FIGURE 19. EQUATION OF A STRAIGHT LINE

values. This was done from the second point of activation to the n - 1 point of activation. This calculation technique eliminated the end points of the curves, which preliminary investigation indicated to have the most variability.

Six relationships for any loop were chosen to be descriptive of what that particular loop was doing during activation. The relationships used were; Fx/Ax, Fy/Fx, Fz/Fx, Mx/Fx, My/Fx, and Mz/Fx. Each relationship is expressed by a value which is the slope for that particular curve.

The Fx/Ax relationship is the only absolute relationship considered. It is a measure of the stiffness of the loop in the principle direction of activation. The other relationships are all relative values, in that they express how a particular force or moment varies with respect to the force in the x direction.

This information therefore describes the force and moment production in three dimensions for any activation distance (as long as the relationship remains linear), and succeeds in reducing the large volume of data on each loop to six numbers.

RESULTS

INTRODUCTION

Table II illustrates the format which will be used to describe the results. All values given in the tables are either the slope values of the particular relationship in question, or the intercepts (H or V) for the curve. The use of the intercepts with the slope is uniquely descriptive of the linear relationship in question. The format of each block in the table is illustrated as follows:

<table>
<tr><td rowspan="2">A</td><td>B</td></tr>
<tr><td>C</td></tr>
</table>

where; A is the slope value, B is the H intercept, and C is the V intercept.

Line one in the tables (Fx/Ax) is the load deflection value of the loop. It indicates the stiffness of the loop being tested and allows a calculation of the amount of x force generated per millimeter of activation, providing the relationship remains linear. It is, therefore, a calculation of the absolute x force generated per millimeter of activation.

Lines two through six in the tables are relative values, in that they express the amount of force or moment generated per gram of x force.

These relative values can also be utilized to quantify the abso-

TABLE II

FORCE AND MOMENT RELATIONSHIPS FOR CENTERED VERTICAL LOOPS, BURSTONE LOOP TESTED AS IN FIG. 16B.

	OPEN VERTICAL LOOP		CLOSED VERTICAL LOOP		OPEN VERTICAL LOOP WITH HELIX		CLOSED VERTICAL LOOP WITH HELIX		L-LOOP		BURSTONE LOOP	
Fx/Δx	+57.77	0/0	+51.36	0/0	+40.43	0/0	+40.95	0/0	+40.02	0/0	+18.86	0/0
Fy/Fx	-.04	0/0	+.02	0/0	.00	0/0	-.02	0/0	-.36	0/0	-.07	0/0
Fz/Fx	-.03	0/0	+.04	0/0	+.02	0/0	+.11	0/0	+.03	0/0	-.15	0/0
Mx/Fx	-.40	0/0	+.50	0/0	+.11	0/0	+1.44	0/0	-1.19	0/0	-1.38	0/0
My/Fx	-3.42	0/0	-4.08	0/0	-3.28	0/0	-3.54	0/0	-3.45	0/0	-3.85	0/0
Mz/Fx	-9.95	0/0	-9.66	0/0	-8.56	0/0	-8.55	0/0	-11.28	0/0	-10.17	0/0

lute force and moment, for any activation (in the linear range) by using the formula,

$$A = ((S \times D) \times R) + V$$

where: A is the absolute force or moment value in question,

S is the slope of the load deflection curve,

D is the amount of activation,

R is the slope of the relative force or moment,

V is the V intercept.

The units of calculation are dependent on the particular relationship in question with Fx/Ax measured in gm./mm., Fy/Fx and Fz/Fx calculated in gm./gm., and all moment values per Fx calculated in gm.-mm./gm.

CENTERED VERTICAL LOOPS

The results for this activation are given in table II. All loops (except the Burstone loop) were tested with the vertical portion of the loop centered between the mounting tubes, such that the distance from the center of the vertical portion of the loop to either mounting tube was 6 mm. The Burstone loop was tested as in figure 16b.

All experimental activations in this block were conducted with a zero offset in the y direction. The principle direction of activation was in the plus x direction, with the Burstone loop activated over a range of 5 mm., and all other vertical loops over a range of 2mm..

The activation of all the loops in table II resulted in a positive force generation in the x direction. The Burstone loop had the lowest slope value (18.8 gm./mm.), while the open vertical loop had the highest value (57.8 gms.). The slope values for the open and closed vertical loop with a helix and the L-loop were similar, and possessed a value approximately twice that of the Burstone loop.

The slope values in the y direction are for the most part very small, with the L-loop possessing the only value of any significance (-.36). Since the loops all possess a V intercept of 0 and very small slope values (with the exception of the L-loop), it can be assumed that the force production in the y direction for all practical purposes is zero. The L-loop on the other hand will produce a negatively directed y force approximately one third the magnitude of the x force (V intercept at 0).

The slope values in the z direction are also very small, with the only possible exceptions being the closed vertical loop with a helix and the Burstone loop. The closed vertical loop with a helix has a positive slope value of .11 gm./gm. while the Burstone has a negative slope value of .15 gm/gm. These slope values would equate to a 4.5 gm./mm. force in the plus z direction for the closed vertical loop with a helix and a 2.8 gm./mm. force in the negative z direction for the Burstone loop. For all practical purposes the slope values for the other loops coupled with a zero V intercept would produce a negligible z force per gram of x force.

The slopes of the rotational effects around the x axis (Mx) varied both in terms of magnitude and direction. The Burstone, open vertical loop, and the L-loop all produced negatively directed slopes. The closed vertical loop, vertical loop with a helix, and the open vertical loop with a helix all produced positively directed slope values. The magnitude of the slope relationships is also varied, ranging from .11 gm.-mm./gm. to 1.44 gm.-mm./gm.

The slope values for the My/Fx relationship are all negatively directed with a range in magnitude of from 3.28 gm.-mm./gm. for the open vertical loop with a helix to 4.08 gm.-mm./gm. for the closed vertical loop. The mean of these values is -3.60 gm.-mm./gm., with a standard deviation of .30, indicating a fair degree of similarity between all the slope values given.

The Mz/Fx relationships are also all negatively directed with values ranging from 8.5 gm.-mm./gm. for the closed vertical loop with a helix to 11.28 gm.-mm./gm. for the L-loop. The values for both loops with a helix are very closely related (with a difference of only .01 gm.-mm./gm.), as are the values for the open and closed vertical loops.

The overall impression from table II is that with the activation of a loop, in the positive x direction, a positive x force is generated. The magnitude of this force depends on the size and the amount of wire incorporated into the loop, and the amount of activation. The forces that result in the y and z direction as a result of this force are for the most part negligible.

The rotational effects on the other hand exhibit variability around the x axis in both direction and magnitude. The magnitude of the slopes of the Mx/Fx relationship is on average less than one-half that of the magnitude of the slopes for the My/Fx relationship.

The rotational effects around the y and z axis are all negative in sign with the magnitude of the moments around the z axis being approximately two and one-half times those around the y axis.

VERTICAL LOOP ONE AND ONE HALF MILLIMETERS FROM THE MODEL TOOTH

The results for this segment of the investigation are given in table III.

In this block, the position of the vertical portion of the loop (except for the Burstone) was changed from a centered position, to one, 1.5 mm. from the model tooth. The Burstone was tested as in figure 16b. All loops were activated as in block one.

All loops when activated, produced a force in the positive x direction. The magnitude of the slope values in this block are on average about 3 gm./mm. higher than the slope values found in block one. The Burstone loop produced similar slope values in both blocks.

All the slope values in the y direction (except for the Burstone and L-loop) are positively directed. The magnitude for these values varied between .24 gm./gm. to .33 gm./gm. with the open vertical loop with a helix having the highest value, while the closed vertical loop with a helix had the lowest value.

The Burstone loop and the L-loop both produced relatively small negatively directed slope values.

The slope values found in the y direction in this block are on average .30gm./gm. higher in value and more positively directed than

TABLE III

FORCE AND MOMENT RELATIONSHIPS FOR VERTICAL LOOPS 1.5 MM. FROM MODEL TOOTH.
BURSTONE LOOP TESTED AS IN 16B.

	OPEN VERTICAL LOOP		CLOSED VERTICAL LOOP		OPEN VERTICAL LOOP WITH HELIX		CLOSED VERTICAL LOOP WITH HELIX		L-LOOP		BURSTONE LOOP	
Fx/Δx	+61.75	0/0	+59.64	0/0	+44.96	0/0	+43.81	0/0	+42.05	0/0	+19.84	0/0
Fy/Fx	+.32	0/0	+.27	0/0	+.33	0/0	+.24	0/0	-.07	0/0	-.04	0/0
Fz/Fx	-.04	0/0	-.06	0/0	-.02	0/0	-.01	0/0	-.03	0/0	-.14	0/0
Mx/Fx	+1.46	0/0	+.97	0/0	+2.04	0/0	+1.09	0/0	-1.01	0/0	-1.48	0/0
My/Fx	-3.19	0/0	-3.39	0/0	-3.60	0/0	-3.39	0/0	-3.48	0/0	-3.75	0/0
Mz/Fx	-6.29	0/0	-7.19	0/0	-5.78	0/0	-6.40	0/0	-8.34	0/0	-10.48	0/0

those found in block one. This trend is evident in all the loops examined in this block (except the Burstone), such that the Fy/Fx slope values in block one have changed from being zero or negatively directed to being positively directed, or in the case of the L-loop with a much smaller negative magnitude.

All the slopes in the z direction are negative in direction. The magnitude of the slope values (except for the Burstone loop) are small varying from .01 to .06 gm./gm. The Burstone loop produced a negative slope of .14 gm./gm.

When compared to the slopes in the z direction in the first block it is evident that there is a trend in all the loops (except the Burstone) for the slope values to become negative. This trend illustrates a change in the direction of the slopes in this block from being positive to becoming negative with aproximately the same magnitude .

Rotational effects around the x axis are varied in both magnitude and direction. The magnitude of the slopes varied between .97 to 2.04 gm.-mm./gm. The slope directions are primarily positive, with the L-loop and the Burstone loop having negatively directed slope values.

No trend in terms of directional change or magnitude can be found when these results are compared to the results in block one, suggesting that there is little effect on the rotation around the x axis when the position of the vertical portion of the loop is changed.

The rotational effects around the y axis are all negatively directed as in the first block. The magnitude of the moments varied between 3.19 gm.-mm./gm. to 3.75 gm.-mm./gm., which again are similar to the values found in block one.

The moments around the z axis are all negatively directed. The magnitude of these moments varied between 5.78 to 10.48 gm.-mm./gm. These values, exhibit an average decrease in the slope values of 2.8 gm.-mm./gm. when compared to the values in table II. This decrease in slope magnitude indicates a reduction in the rotational effects around the z axis when the position of the vertical loop is moved closer to the model tooth.

The total effect found with the change in position of the vertical portion of the loop may therefore be summarized as producing a slight increase in x force, with an increase in the magnitude of the slope relationship Fy/Fx, and a decrease in the value of the relationship Mz/Fx.

RESULTS OF OFFSETTING Y.

As explained in the section on experimental method, x activation in block three was performed for each of a number of y offsets. The y offsets ranged from -1 mm. to +1 mm in .5 mm. increments. The amount of x activation was the same as for blocks one and two. All loops in this block were positioned as in block two..

The results for the straight vertical loop are listed in tables IV to VII. The results for the L-loop are given in table VIII while those for the Burstone can be found in table IX.

The results for the closed vertical loop are presented in graphic

TABLE IV

FORCE AND MOMENT RELATIONSHIPS FOR CLOSED VERTICAL LOOP (1.5 MM. FROM MODEL TOOTH) WITH VERTICAL MISALIGNMENT.

	-1 MM. Y OFFSET		-.5 MM. Y OFFSET		0 MM. Y OFFSET		+.5 MM. Y OFFSET		+1 MM. Y OFFSET		
Fx/Ax	+59.04	+.36 -18.9	+59.76	+.22 -12.2	+57.23	0 0	+60.02	+.07 +5.45	+61.82	-.24 +16.02	X̄ = +59.57 S.D. = +1.60
Fy/Fx	+.32	+162.6 -51.8	+.29	+91.9 -26.9	+.30	0 0	+.32	-91.1 +32.7	+.29	-251.9 +69.9	X̄ = -.30 S.D. = +.015
Fz/Fx	-.03	- +1.44	-.04	- +.75	-.03	0 0	-.03	- -1.99	+.02	- -2.66	X̄ = -.02 S.D. = +.02
Mx/Fx	+1.06	+186.6 -231.08	+.87	+145.6 -119.9	+.82	0 0	+1.08	-130.39 +106.4	+1.03	-190.4 +226.1	X̄ = +.97 S.D. = +.12
My/Fx	-3.48	0 0	-3.61	-2.6 -23.9	-3.48	0 0	-3.42	0 0	-3.0	+3.99 +26.6	X̄ = -3.42 S.D. = +.19
Mz/Fx	-8.04	-37.24 -305.9	-7.66	-19.68 -186.2	-7.49	0 0	-7.01	+29.3 +202.6	-6.92	+63.9 +413.33	X̄ = -7.42 S.D. = +.46

TABLE V

FORCE AND MOMENT RELATIONSHIPS FOR OPEN VERTICAL LOOP (1.5 MM. FROM MODEL TOOTH)
WITH VERTICAL MISALIGNMENT.

	-1 MM. Y OFFSET		-.5 MM. Y OFFSET		0 MM. Y OFFSET		+.5 MM Y OFFSET		+1 MM. Y OFFSET		
Fx/Ax	+62.90	+.49	+60.80	+.3	+60.07	0	+62.68	-.08	+63.19	-.25	$\bar{X}$ = +61.92
		-32.5		-19.09		0		+5.45		+16.36	S.D. = +1.39
Fy/Fx	+.38	+136.7	+.34	+86.45	+.31	0	+.37	-89.03	+.32	-211.61	$\bar{X}$ = +.34
		-56.36		-28.18		0		+30.9		+69.99	S.D. = +.03
Fz/Fx	-.01	-	-.01	-	+.01	0	+.03	-	-.01	-	$\bar{X}$ = +.002
		+1.63		+.36		0		-1.81		-2.72	S.D. = +.017
Mx/Fx	+1.29	+126.6	+.96	+71.9	+.92	0	+1.51	-127.9	+1.04	-209.3	$\bar{X}$ = +1.144
		-186.6		-93.3		0		+119.9		+245.3	S.D. = +.25
My/Fx	-3.26	-3.99	+3.17	-.66	-3.22	0	-3.13	+7.9	-3.28	+11.3	$\bar{X}$ = =3.21
		-21.3		-5.33		0		+26.6		+66.6	S.D. = +.062
Mz/Fx	-6.68	-43.9	-6.88	-.20	-6.44	0	-6.18	+35.3	-5.89	+77.33	$\bar{X}$ = -6.41
		-306.6		-133.3		0		+226.6		+501.3	S.D. = +.393

TABLE VI

FORCE AND MOMENT RELATIONSHIPS FOR THE OPEN VERTICAL LOOP WITH HELIX (1.5 MM. FROM MODEL TOOTH) WITH VERTICAL MISALIGNMENT.

	-1 MM. Y OFFSET		-.5 MM. Y OFFSET		0 MM. Y OFFSET		+.5 MM. Y OFFSET		+1 MM. Y OFFSET		
Fx/Ax	+46.86	+.41 +19.0	+45.68	+.23 +10.54	+45.01	0 0	+45.87	-.12 +4.54	+45.75	-.25 +10.72	$\bar{X}$ = +45.8 S.D. = +.66
Fy/Fx	+.43	+116.1 -49.9	+.36	+65.8 -25.1	+.34	0 0	+.37	-57.41 +21.8	+.33	-184.5 +52.7	$\bar{X}$ = +.29 S.D. = +.13
Fz/Fx	-.05	- -3.45	-.03	- -2.5	-.02	0 0	-.02	- +.72	+.01	- +1.99	$\bar{X}$ = -.02 S.D. = +.018
Mx/Fx	+.88	+119.3 -155.8	+1.01	+67.4 -83.1	+1.04	0 0	+1.05	-64.5 +77.9	+1.08	-127.0 +171.4	$\bar{X}$ = +1.01 S.D. = +.078
My/Fx	-3.26	-38.70 -11.6	-3.18	-2.5 -2.7	-2.84	0 0	-2.90	+33.5 +7.48	-2.62	+51.6 +14.3	$\bar{X}$ = -2.98 S.D. =+.29
Mz/Fx	-5.51	-263.2 -47.7	-5.84	-136.7 -24.5	-5.36	0 0	-5.41	+159.9 +29.9	-4.33	+335.4 +70.3	$\bar{X}$ = -5.29 S.D. = +.56

TABLE VII

FORCE AND MOMENT RELATIONSHIPS FOR THE CLOSED VERTICAL LOOP WITH HELIX (1.5 MM. FROM MODEL TOOTH) WITH VERTICAL MISALIGNMENT.

	-1 MM. Y OFFSET		-.5 MM. Y OFFSET		0 MM. Y OFFSET		+.5 MM. Y OFFSET		+1 MM. Y OFFSET		
Fx/Ax	+46.52	+.38 -18.18	+44.63	+.19 -8.1	+41.88	0 0	+42.34	-.15 +5.8	+43.76	-.21 +8.7	$\bar{X}$ = +43.8 S.D. = +1.86
Fy/Fx	+.45	+118.6 -55.5	+.33	+66.1 -26.1	+.25	0 0	+.24	-114.6 +27	+.26	-201.9 +56.4	$\bar{X}$ = +.30 S.D. = +.088
Fz/Fx	+.09	- -.05	+.08	- -1.44	.00	0 0	-.02	- -1.35	+.07	- -1.8	$\bar{X}$ = +.044 S.D. = +.05
Mx/Fx	+2.79	+80 -213.3	+2.09	+60 -138.7	+1.24	0 0	+.83	-49.3 +80	+1.90	-53.3 +117.3	$\bar{X}$ = +1.77 S.D. = +.76
My/Fx	-3.38	+2.7 +7.9	-4.24	+9.1 +31.9	-3.67	0 0	-2.88	-5.8 -21.3	-3.05	-2.7 -34.6	$\bar{X}$ = -3.44 S.D. = +.54
Mz/Fx	-6.23	-49.9 -319.9	-6.31	-25.3 -159.9	-6.93	0 0	-6.46	+27.9 +162.6	-6.17	+59.2 +346.6	$\bar{X}$ = -6.4 S.D. = +.29

form to provide a visual interpretation of these results. The trends that can be seen in these graphs (fig. 20 to 25), are also found for the other straight vertical loops even though the slope values and intercepts may differ. The results for the L-loop are also graphed (fig. 26 to 31) to show the effects of the horizontal component on the force production. The results of the Burstone loop, exhibit the same trends as those of the L-loop.

The straight vertical loops when activated all produced postive slope values for Fx/Ax. As figure 20 illustrates these graphs are close to being parallel to one another with markedly different V intercepts. The graphs for the positive y offsets all have positve V intercepts, while those of the negatively directed offsets all possess negative V intercepts. The net effect of this would be that even with zero millimeters of x activation it is possible to have a force in the x direction. Depending on the direction of the y offset, it may be possible to generate a force which is opposite in direction to that which is desired, (see graph for the -1 mm. y offset figure 20).

It is also evident that if a particular force value is desired and there is a y offset, the amount of activation required to produce this force level will not be the same as for a loop with zero offset.

The H intercepts for these graphs also indicate that it is possible to have a situation in which there is an x activation of the loop, but no force produced as a result of this activation, (see graph for the -1 mm. y offset figure 20).

Due to the initial force value with a +1 mm. y offset, the full

FIGURES 20 TO 25

Force and moment relationships for the closed vertical loop (1.5 mm. from the model tooth) with positive and negative misalignment of the end in the vertieal (y) plane.

The following legend will apply to figures 20 to 25:

+1 mm, y offset

+.5 mm. y offset

0 mm. y offset

-.5 mm. y offset

-1 mm. y offset

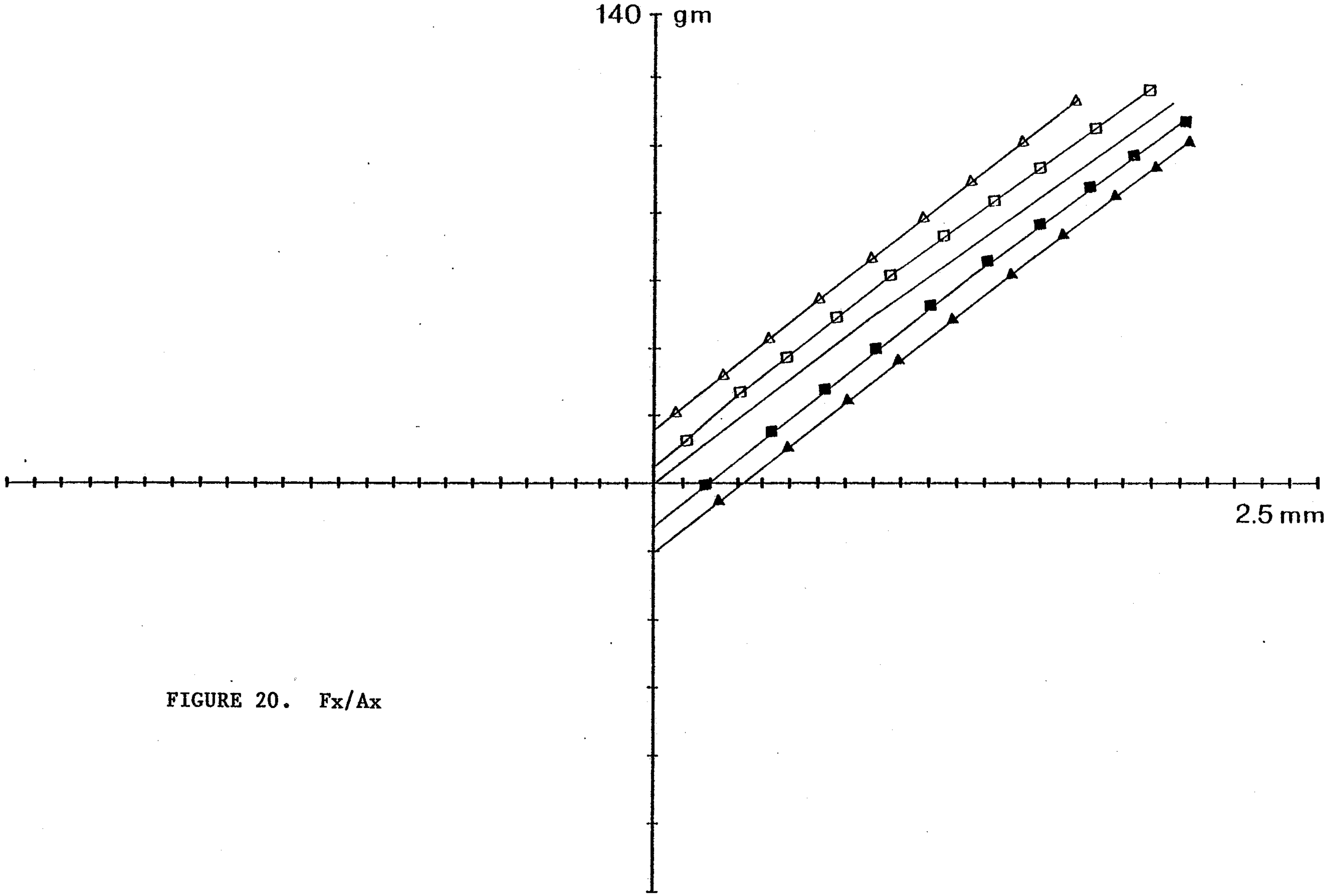


FIGURE 20. Fx/Ax

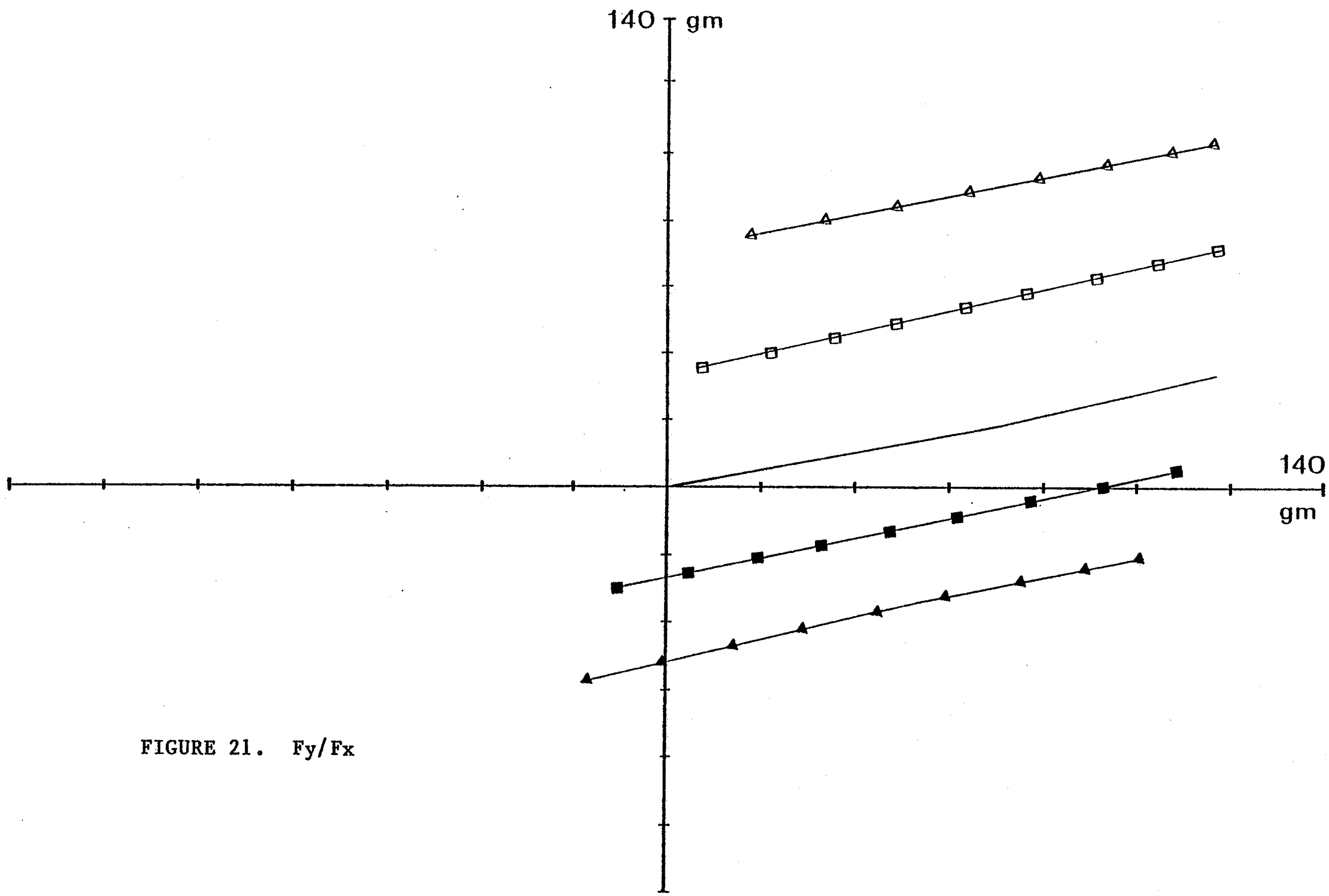


FIGURE 21. Fy/Fx

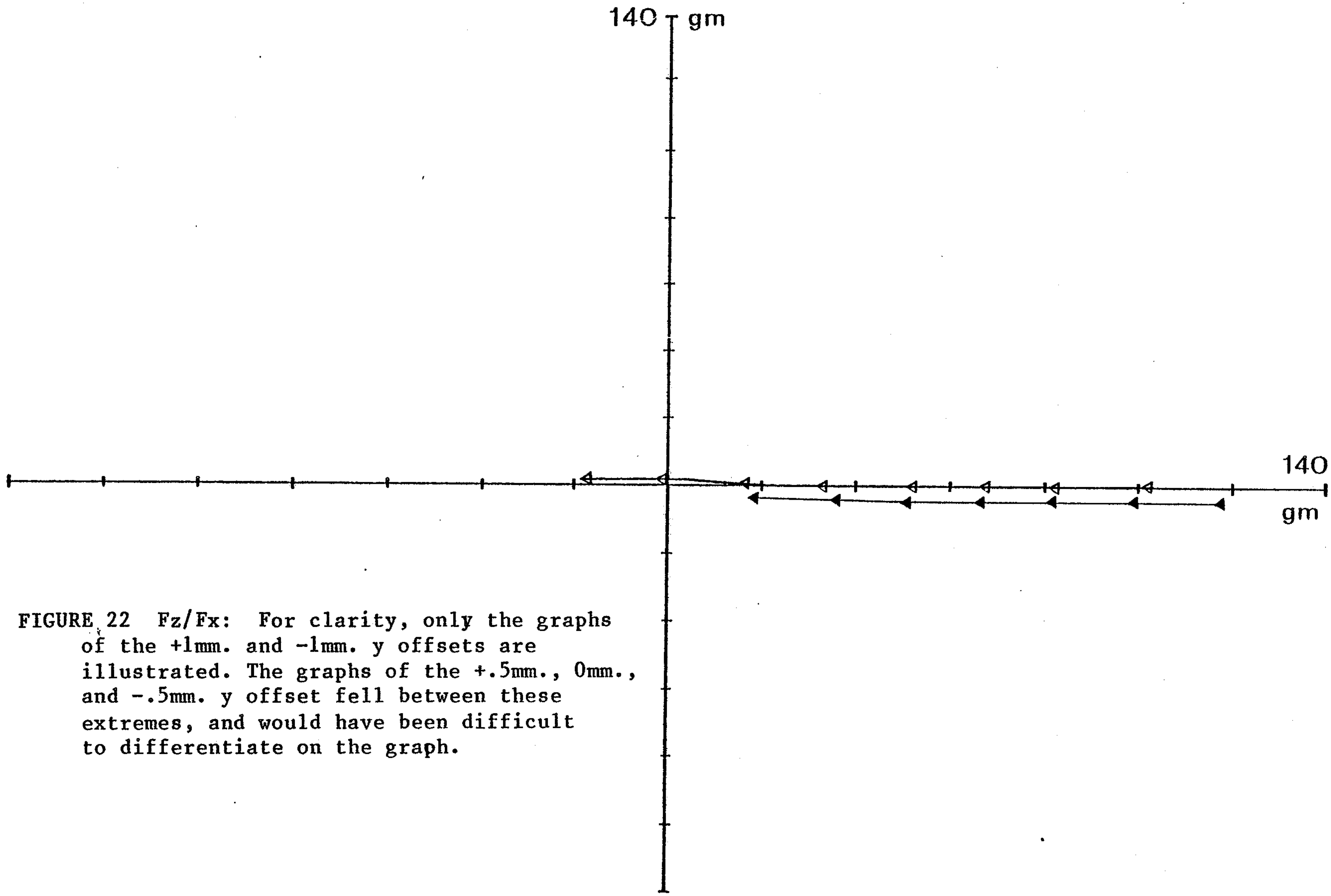


FIGURE 22 Fz/Fx: For clarity, only the graphs of the +1mm. and -1mm. y offsets are illustrated. The graphs of the +.5mm., 0mm., and -.5mm. y offset fell between these extremes, and would have been difficult to differentiate on the graph.

range of the x activation was not applied as the maximum force level of the instrument (130 gm.) would have been exceeded.

The graphs for the Fy/Fx ratio indicate a parallelism, and hence a consistancy in slope values between the graphs for the various y offsets. The slope values of this ratio for all the straight vertical loops are positive in direction, with a value approximately one third that of the force in the x direction. What is primarily evident in figure 21 are the V intercept values, which show that even with zero millimeters of x activation, y forces are generated. These V intercepts indicate that the straight vertical loops are rigid in the vertical plane, with small variations in the y position leading to the production of y forces.

The slope values for the Fz/Fx relationships are all very small, and similar. The small slope values indicate that the force produced in the z direction per gram of x force is insensitive to changes in the y offsets. The small y intercepts, coupled with the small slope values, for all practical purposes, allows us to consider the effects of the z force as being almost non-existant.

The net effect on the force production of the straight vertical loops, due to the y offsets may therefore be summarized by the realization that even with zero millimeters of loop activation (x direction) it is possible to have forces acting in both the x and y direction which could influence the tooth to be moved.

The effects on the rotations around the three axes seem to parallel the effects found on the three forces.

The Mx/Fx relationship for the closed vertical loop is illustrated in figure 23. This relationship tends to exhibit more variability in slope value but nevertheless, a parallelism is evident between the graphs. The effect of the y offsets, is to produce an offsetting of the graphs, so that even with 0 grams of x force, a moment around the x axis is possible (ie. positive or negative V intercept). The slope of these graphs also indicates that there is not much of change in the moment around the x axis as the x force increases.

The moment around the y axis (fig. 24) seems to be relatively insensitive to changes in the y offset. The primary effect on this moment would seem to come from the x activation and not the y offsets.

The rotational effect around the z axis (fig. 25) is sensitive to both the y offsets, as indicated by the distance between the graphs, and the x activation, as indicated by the slopes of the curves. The V intercepts of the graphs show that it is possible to have a moment produced even with zero grams of x force. The H intercept on the other hand indicates that it is not only possible to have zero moment produced with force in the x direction, but also that it is possible for the moment to change its direction (see +1 mm. y offset in figure 25).

The total effect therefore, of having a misalignment of the ends of a straight vertical loop in the vertical plane is that even with zero millimeters of x activation it is still possible to have quite substantial forces and moments, acting on the cuspid.

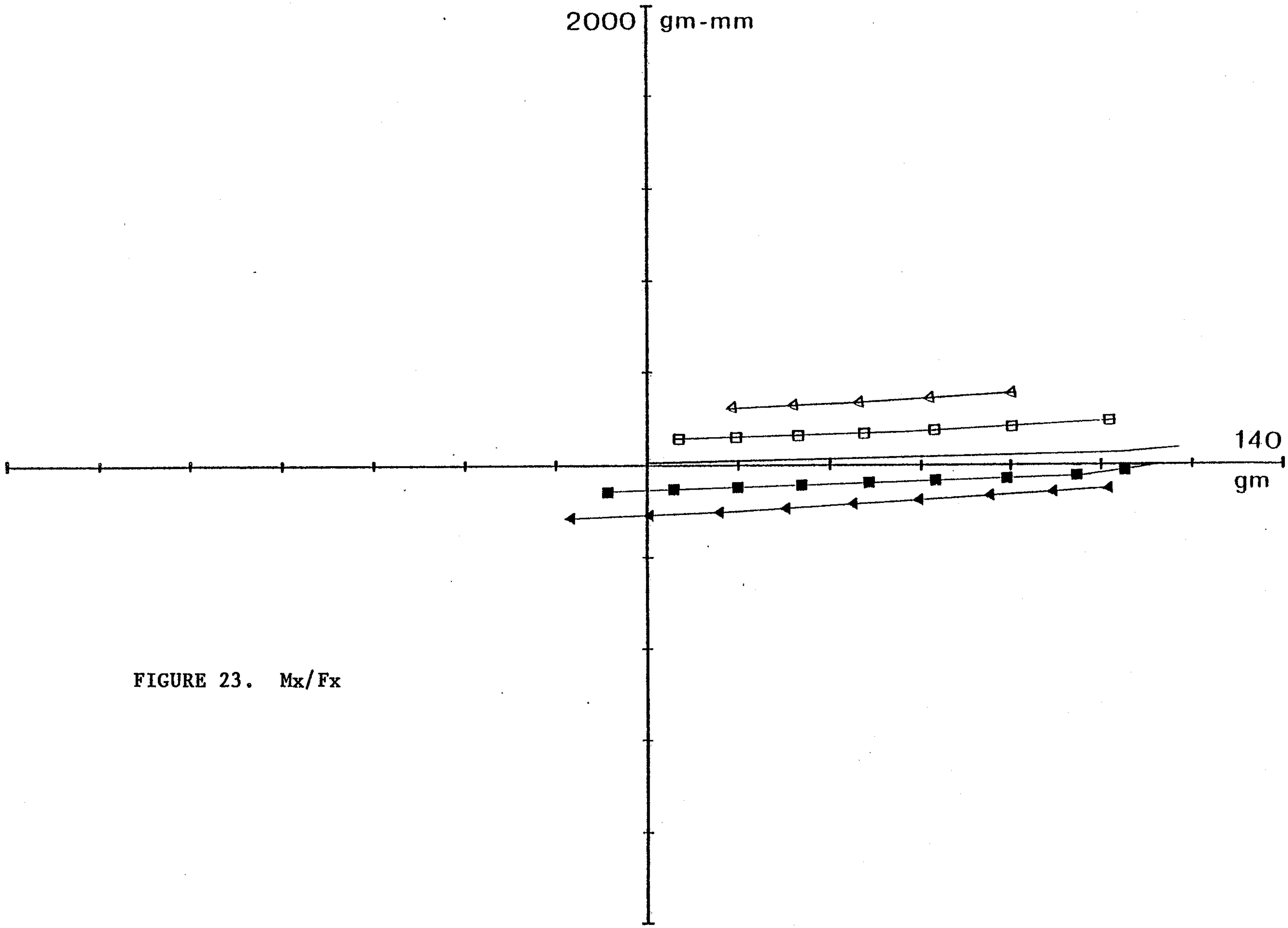


FIGURE 23. Mx/Fx

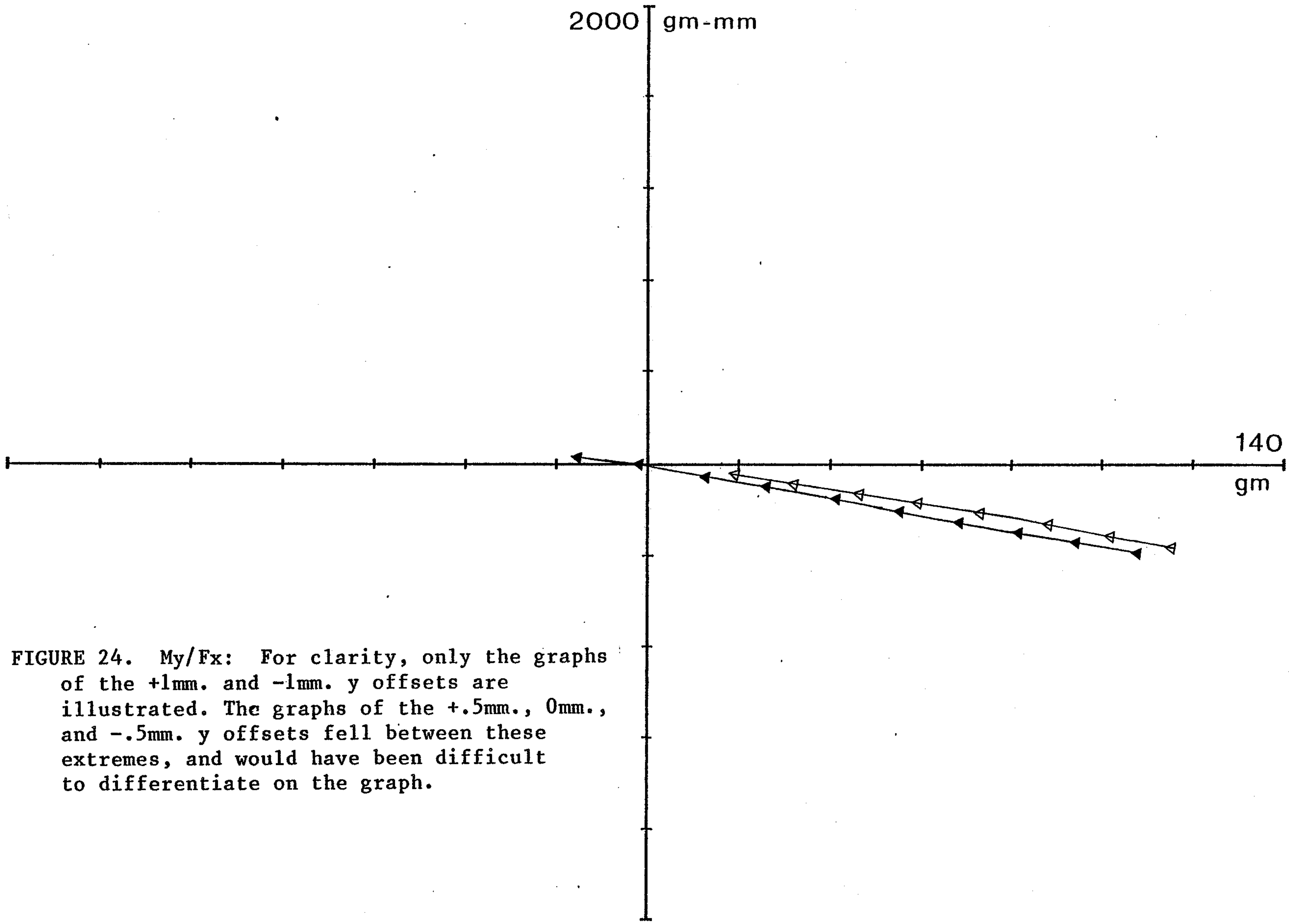


FIGURE 24. My/Fx: For clarity, only the graphs of the +1mm. and -1mm. y offsets are illustrated. The graphs of the +.5mm., 0mm., and -.5mm. y offsets fell between these extremes, and would have been difficult to differentiate on the graph.

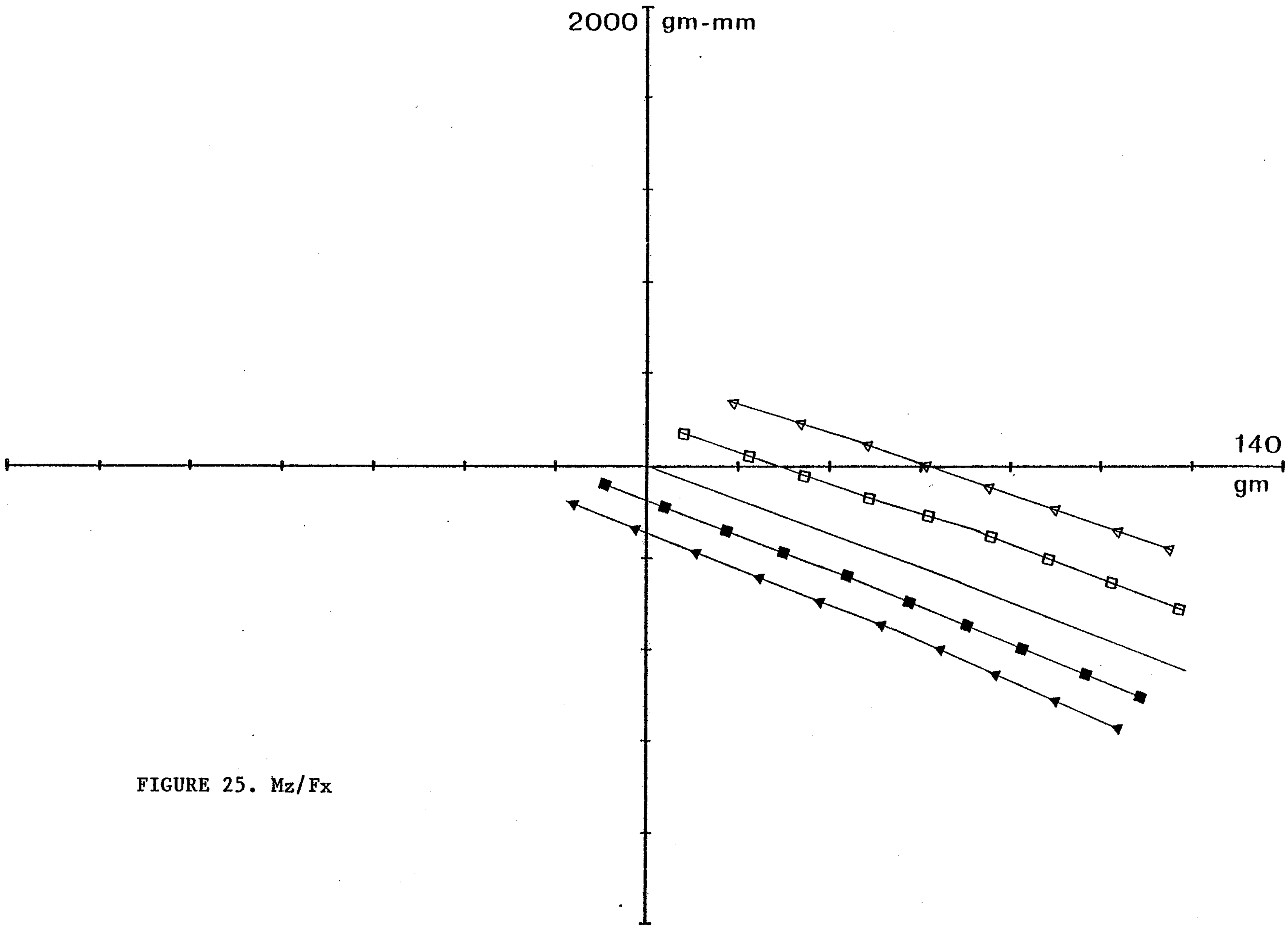


FIGURE 25. Mz/Fx

The results for the Burstone appliance and for the L-loop differ significantly from those just given for the vertical loops in so far as their reaction to the y-offsets is concerned. The results for the L-loop have been graphed (fig. 26 to 31) since its dimensions are similar to the straight vertical loops, with the main difference being the 7 mm. horizontal component of wire. This component should allow for more flexibility of the loop in the vertical plane. The results for the Burstone loop (table IX) exhibit the same trends as those of the L-loop (table VIII), but with different slope values.

The activation of the L-loop in the x direction resulted in the production of positive slope values for Fx/Ax as was found for the straight vertical loop. As figure 26 illustrates, the slope values for all the offsets are similar with the various graphs virtually indistinguishable from one another. If figure 26 is compared to figure 20, it can be seen that the variation in Fx due to the y offsets that is found in figure 20 is lacking in figure 26. This indicates, that the L-loop produces smaller changes in Fx due to misalignment of the ends of the loop than do the straight vertical loops.

The effects of the y offsets on the force production in the y direction (figure 27) is to offset these graphs in a similar fashion to that found for the straight vertical loops. In this case it may be noted that Fy remains constant as Fx is taken over its normal activaton range. The V intercepts for the L-loop are approximately 20% smaller than for the straight vertical loops, indicating that this loop is slightly less sensitive to changes in the y direction than the straight vertical loops.

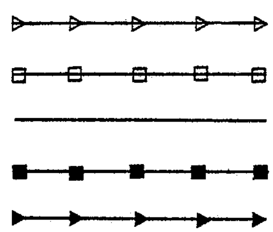
TABLE VIII

FORCE AND MOMENT RELATIONSHIPS FOR THE L-LOOP (1.5 MM. FROM MODEL TOOTH) WITH VERTICAL MISALIGNMENT.

	-1 MM. Y OFFSET		-.5 MM. Y OFFSET		0 MM. Y OFFSET		+.5 MM. Y OFFSET		+1 MM. Y OFFSET		
Fx/Ax	+40.31	0 / 0	+42.98	0 / 0	+43.47	0 / 0	+43.30	0 / 0	+45.16	+.05 / -2.4	$\bar{X}$ = +43.0 S.D. = +1.74
Fy/Fx	+.05	- / -47.27	-.02	- / -24.7	-.02	0 / 0	-.03	- / +29.0	-.09	- / +54.5	$\bar{X}$ = -.02 S.D. = +.049
Fz/Fx	-.04	0 / 0	-.03	0 / 0	-.04	0 / 0	-.03	0 / 0	-.04	-2.5 / -	$\bar{X}$ = -.04 S.D. = +.005
Mx/Fx	+.46	- / -186.6	-.28	- / -99.3	+.08	0 / 0	+.22	- / +104	-.55	- / +221.3	$\bar{X}$ = -.014 S.D. = -.40
My/Fx	-3.36	0 / 0	-3.58	0 / 0	-3.52	0 / 0	-3.42	0 / 0	-2.94	-7.2 / -10.6	$\bar{X}$ = -3.36 S.D. = +.25
Mz/Fx	-7.52	-43.4 / -320.5	-7.84	-25.1 / -198.6	-7.65	0 / 0	-7.86	+22.1 / +158.9	-7.74	+45.1 / +344.3	$\bar{X}$ = -7.82 S.D. = +.14

FIGURES 26 TO 31

Force and moment relationships for the L-loop (1.5 mm. from the model tooth) with positive and negative misalignment of the end in the vertical (y) plane. The following legend will apply to figures 26 to 31:



+1 mm. y offset

+.5 mm. y offset

0 mm. y offset

-.5 mm. y offset

-1 mm. y offset

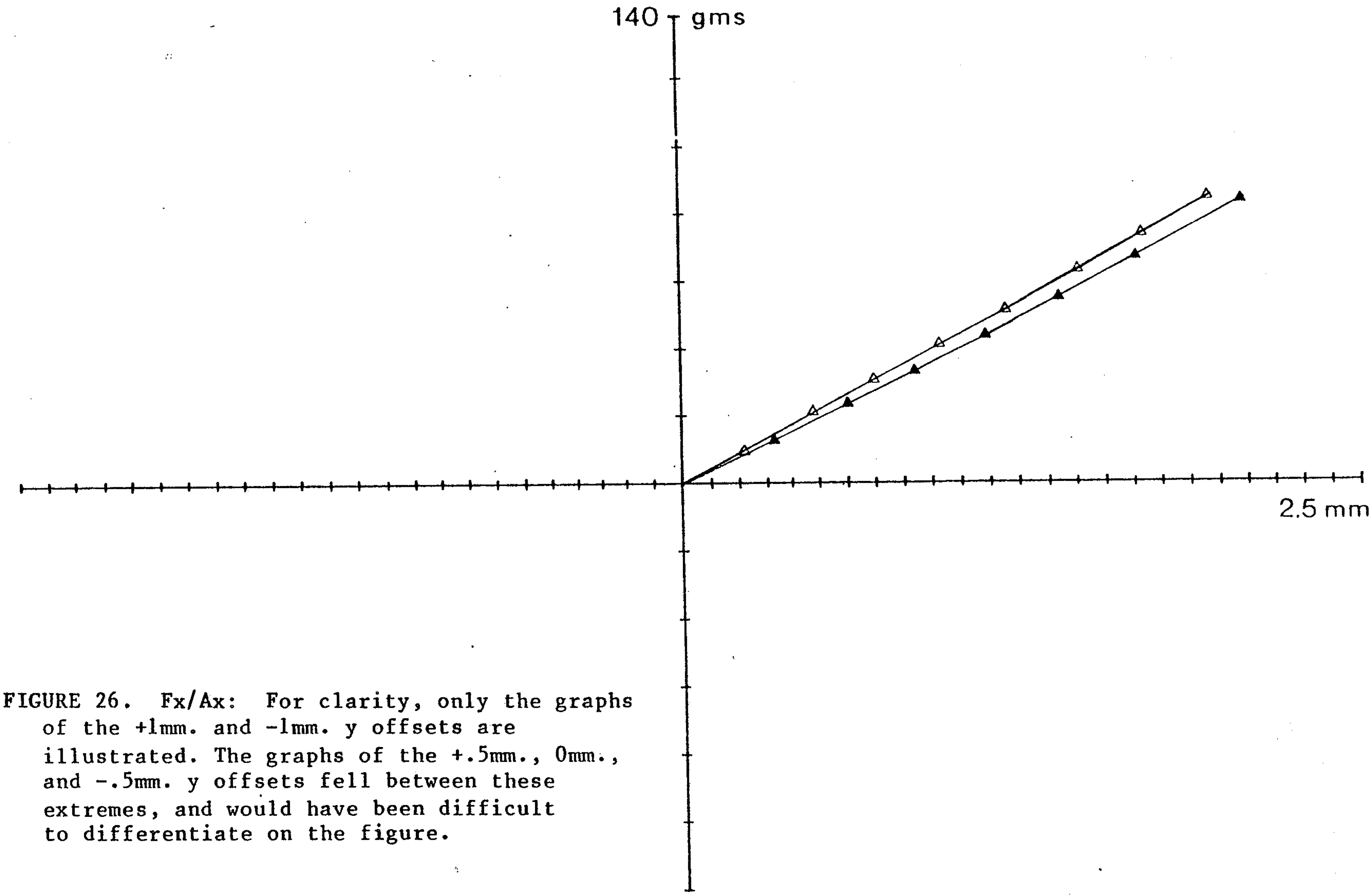


FIGURE 26. Fx/Ax: For clarity, only the graphs of the +1mm. and -1mm. y offsets are illustrated. The graphs of the +.5mm., 0mm., and -.5mm. y offsets fell between these extremes, and would have been difficult to differentiate on the figure.

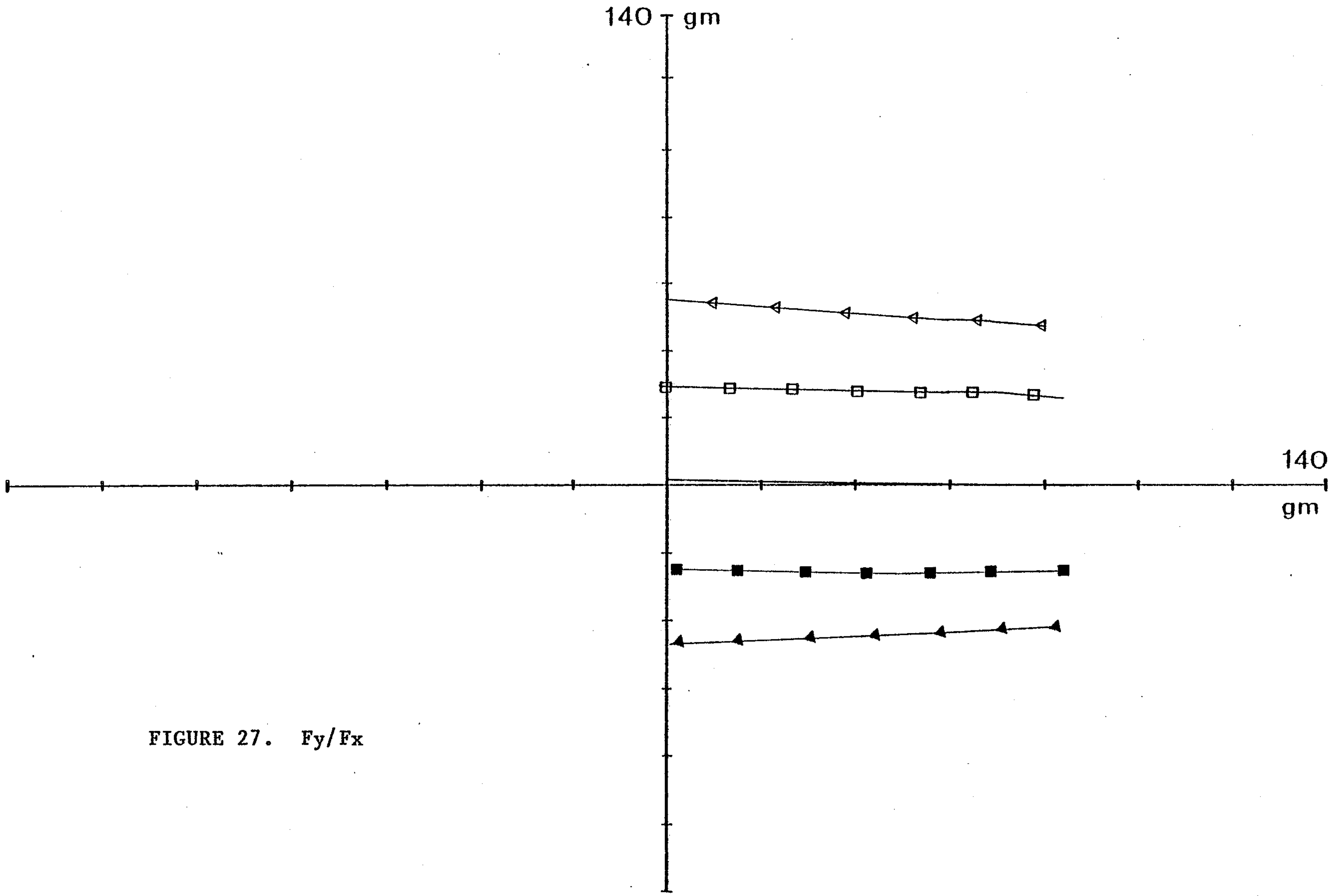


FIGURE 27. Fy/Fx

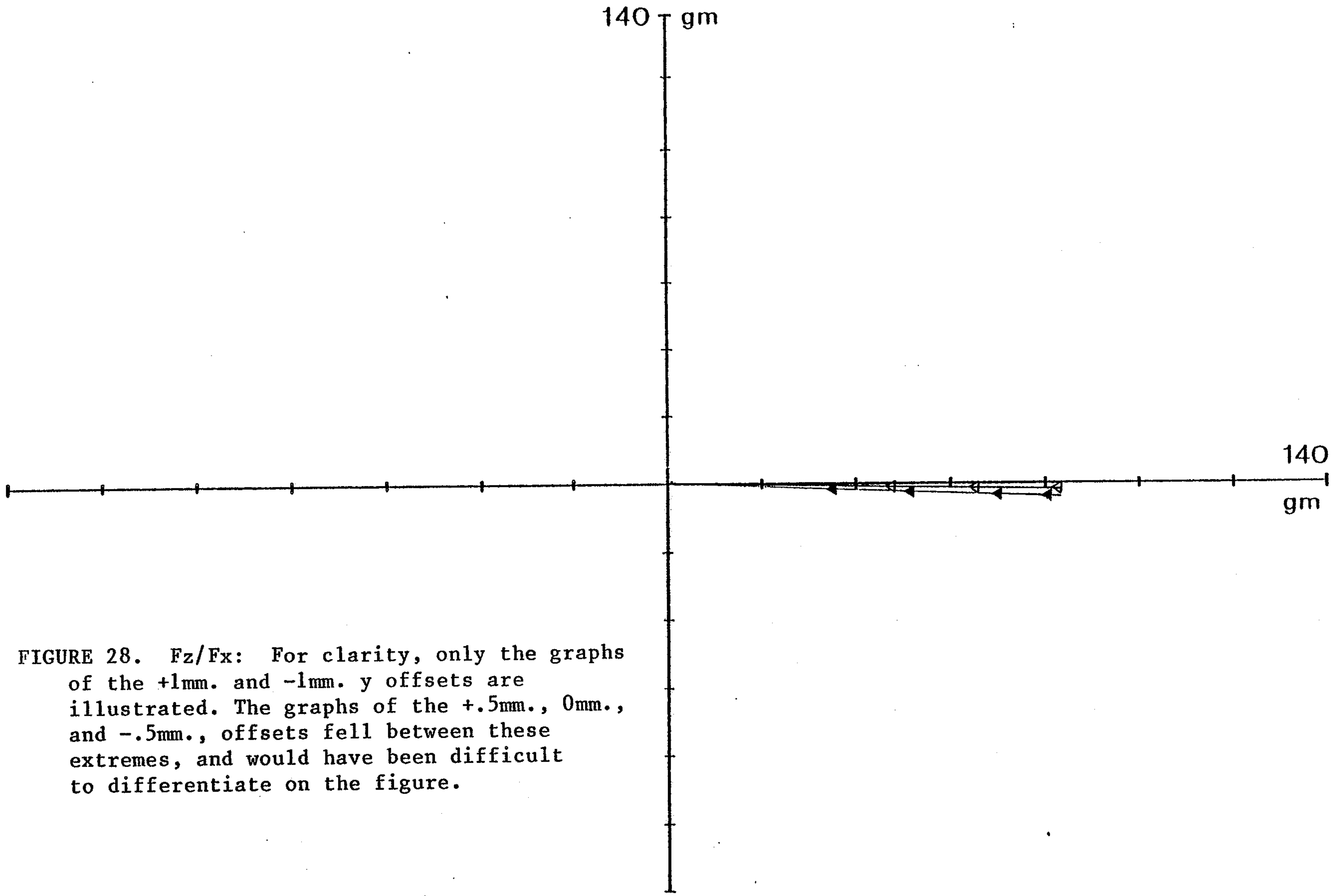


FIGURE 28. Fz/Fx: For clarity, only the graphs of the +1mm. and -1mm. y offsets are illustrated. The graphs of the +.5mm., 0mm., and -.5mm., offsets fell between these extremes, and would have been difficult to differentiate on the figure.

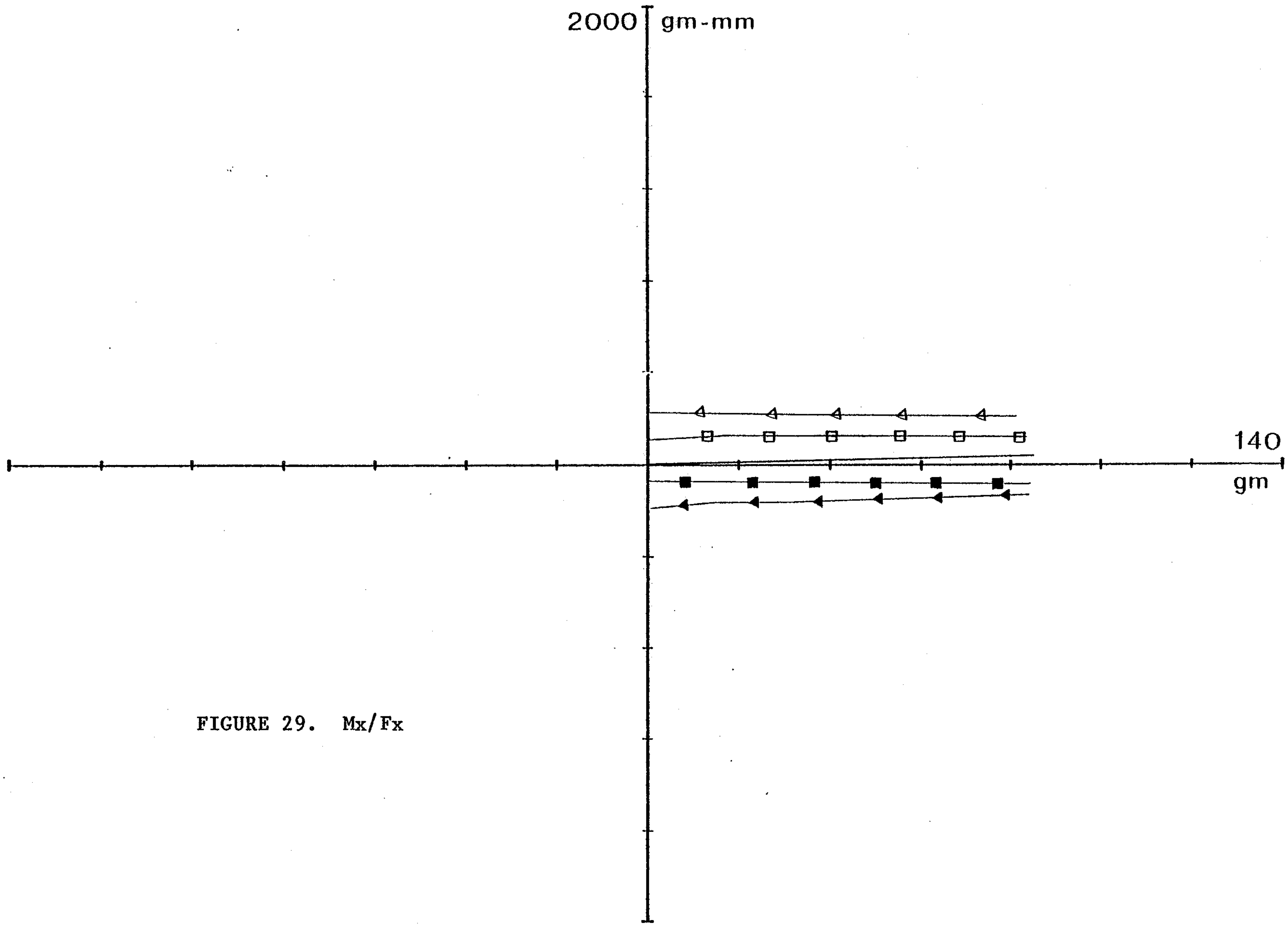


FIGURE 29. Mx/Fx

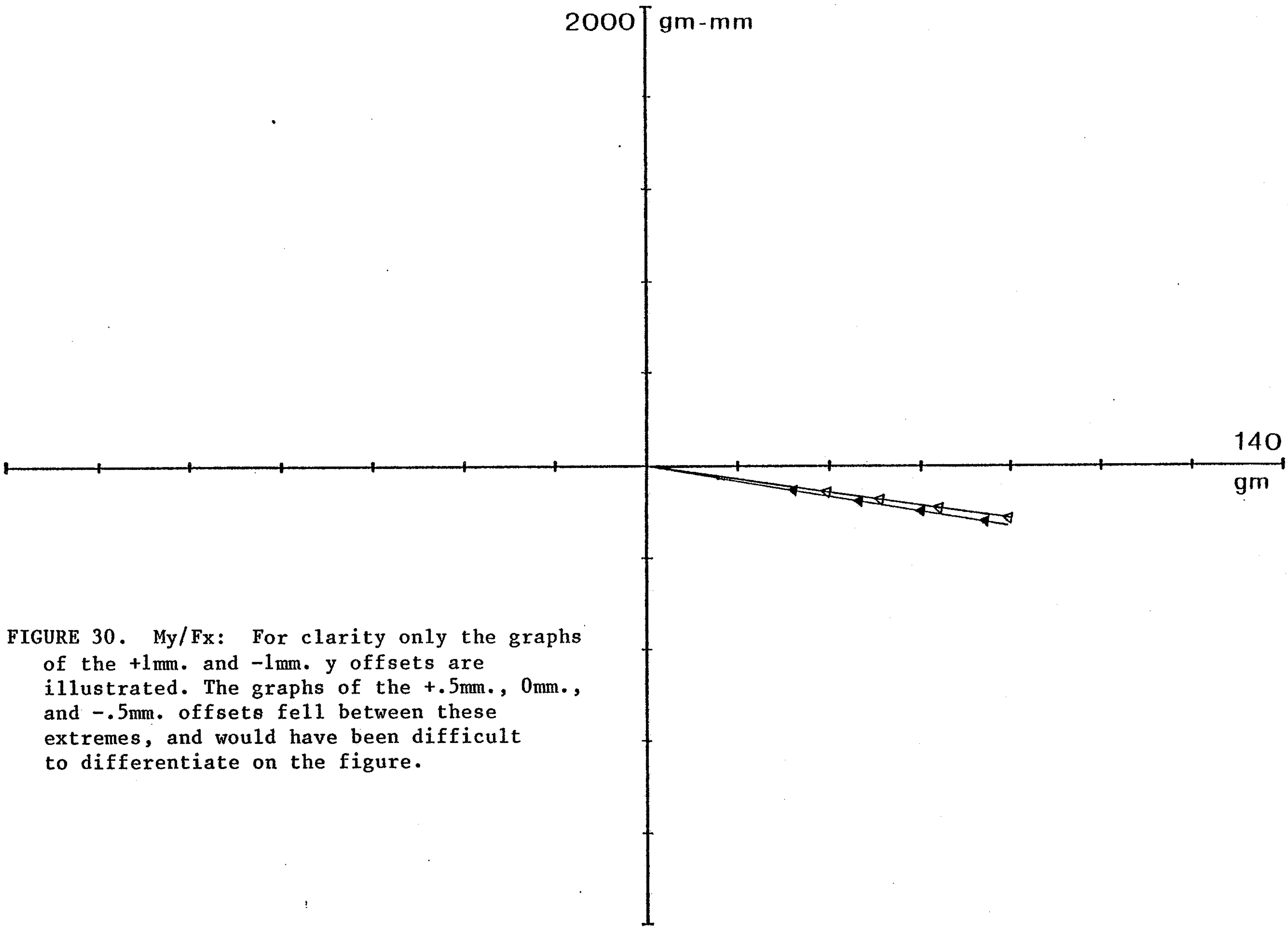


FIGURE 30. My/Fx: For clarity only the graphs of the +1mm. and -1mm. y offsets are illustrated. The graphs of the +.5mm., 0mm., and -.5mm. offsets fell between these extremes, and would have been difficult to differentiate on the figure.

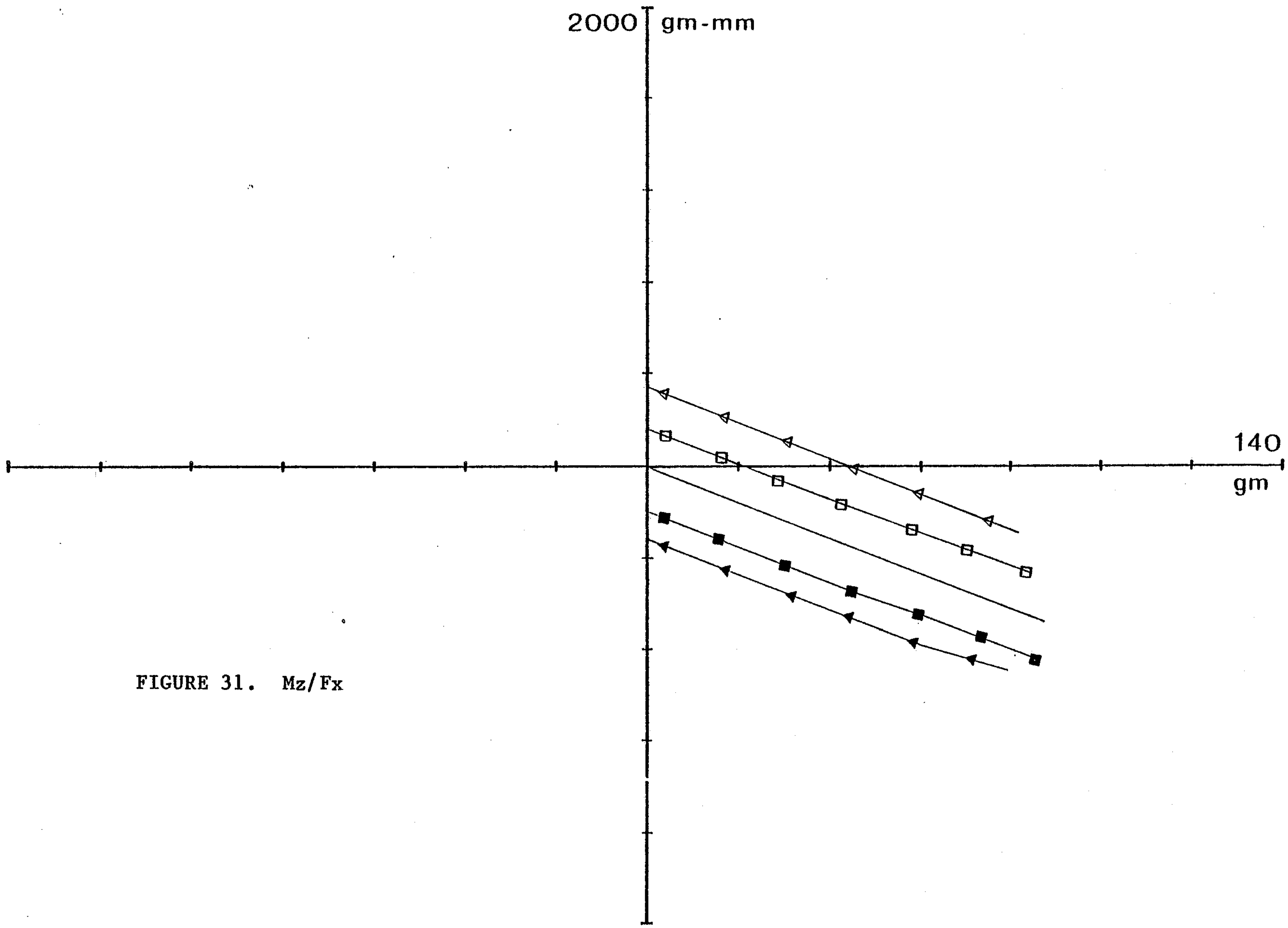


FIGURE 31. Mz/Fx

TABLE IX

FORCE AND MOMENT RELATIONSHIPS FOR THE BURSTONE LOOP (AS IN FIG. 16B) WITH VERTICAL MISALIGNMENT.

	-1 MM. Y OFFSET		-.5 MM. Y OFFSET		0 MM. Y OFFSET		+.5 MM. Y OFFSET		+1 MM. Y OFFSET		
Fx/Ax	+18.47	+1.4 / -19.9	+18.98	+.47 / -.36	+19.65	0 / 0	+19.75	0 / 0	+19.83	0 / 0	$\bar{X}$ = +19.33 S.D. = +.50
Fy/Fx	-.03	- / -12.6	-.05	- / -5.4	-.05	0 / 0	-.05	- / +5.1	-.06	- / +10.0	$\bar{X}$ = -.048 S.D. = +.010
Fz/Fx	-.12	0 / 0	-.10	0 / 0	-.12	0 / 0	-.12	0 / 0	-.11	0 / 0	$\bar{X}$ = -.11 S.D. = +.009
Mx/Fx	-1.39	-97.8 / -123.8	-1.55	-40.2 / -64.5	-1.37	0 / 0	-2.14	+21.9 / +46.4	-1.63	+45.8 / +67.0	$\bar{X}$ = -1.6 S.D. = +.31
My/Fx	-3.78	0 / 0	-3.92	0 / 0	-3.87	0 / 0	-3.96	0 / 0	-3.70	0 / 0	$\bar{X}$ = -3.85 S.D. = +.10
Mz/Fx	-11.08	-11.3 / -152.2	-10.84	-5.4 / -74.8	-10.68	0 / 0	-10.44	+4.5 / +38.7	-10.61	+9.6 / +126.4	$\bar{X}$ = -10.7 S.D. = +.24

The force production in the z direction (figure 28) due to x and y activation is virtually zero. This is comparable to the results found for the straight vertical loops.

The moment production around the x axis (figure 29) reveals the same type of offset pattern found in the curves for the straight vertical loops. The V intercepts for the L-loop show again, that even with zero grams of x force, there is still a moment production around the x axis as a result of offsetting y.

The rotational effects around the y axis (figure 30) have the same type of relationship as that found for the straight vertical loops (figure 24), indicating that the y offsets produce little rotational effects around the y axis.

The moment production around the z axis (figure 31) exhibits the same pattern as that of the straight vertical loops (figure 25).

If a comparison is made between the straight vertical loops, and those with horizontal components, the only difference seems to be the effects on the Fx/Ax relationship and the slopes of the Fy/Fx relationship, with little other differences (in terms of visible trends) being noticeable.

EFFECTS OF GABLE BENDS

The results of incorporating anti-tip and anti-rotation gable bends into the verical loops, and pre-activation bends into the Burstone loop are given in table X . Figures 32 to 37 illustrate the effects of the gable bends on the open vertical loop, these effects

TABLE X

FORCE AND MOMENT RELATIONSHIPS FOR THE OPEN VERTICAL LOOP AND BURSTONE LOOP WITH PREACTIVATION.

	OPEN VERTICAL LOOP						BURSTONE LOOP					
	0 DEGREE		30 DEGREE ANTI-TIP		30 DEGREE ANTI-ROTATION		0 DEGREE		90 DEGREE ANTI-TIP		180 DEGREE ANTI-ROTATION	
Fx/Ax	+61.75	0 0	+64.01	0 0	+65.55	0 0	+19.84	0 0	+20.98	0 0	+18.87	0 0
Fy/Fx	+.32	0 0	+.35	-78 +31.8	+.33	0 0	-.04	0 0	-.06	- -31.2	-.07	0 0
Fz/Fx	-.04	0 0	-.01	0 0	-.02	- -18.8	-.14	0 0	-.11	0 0	-.20	+154.2 +33.3
Mx/Fx	+1.46	0 0	+1.50	-63.2 +119.9	+1.29	- -30.6	-1.48	0 0	-1.79	- -26.6	-2.16	+137.9 +386.6
My/Fx	-3.19	0 0	-3.55	0 0	-3.47	+99.3 +359.9	-3.75	0 0	-3.97	0 0	-3.99	+103.4 +412.9
Mz/Fx	-6.29	0 0	-6.86	+78.7 +493.3	-6.75	0 0	-10.48	0 0	-10.16	+10.3 +106.6	-9.81	-5.16 +79.9

FIGURES 32 TO 37

Force and moment relationships for the open vertical loop (1.5 mm. from the model tooth) with 30 degree anti-tip and anti-rotation gable bends.

The following legend will apply to figures 32 to 37:

— — — — — — —	0 degree gable bend
——————————	30 degree anti-tip gable bend
—·—·—·—·—	30 degree anti-rotation gable bend

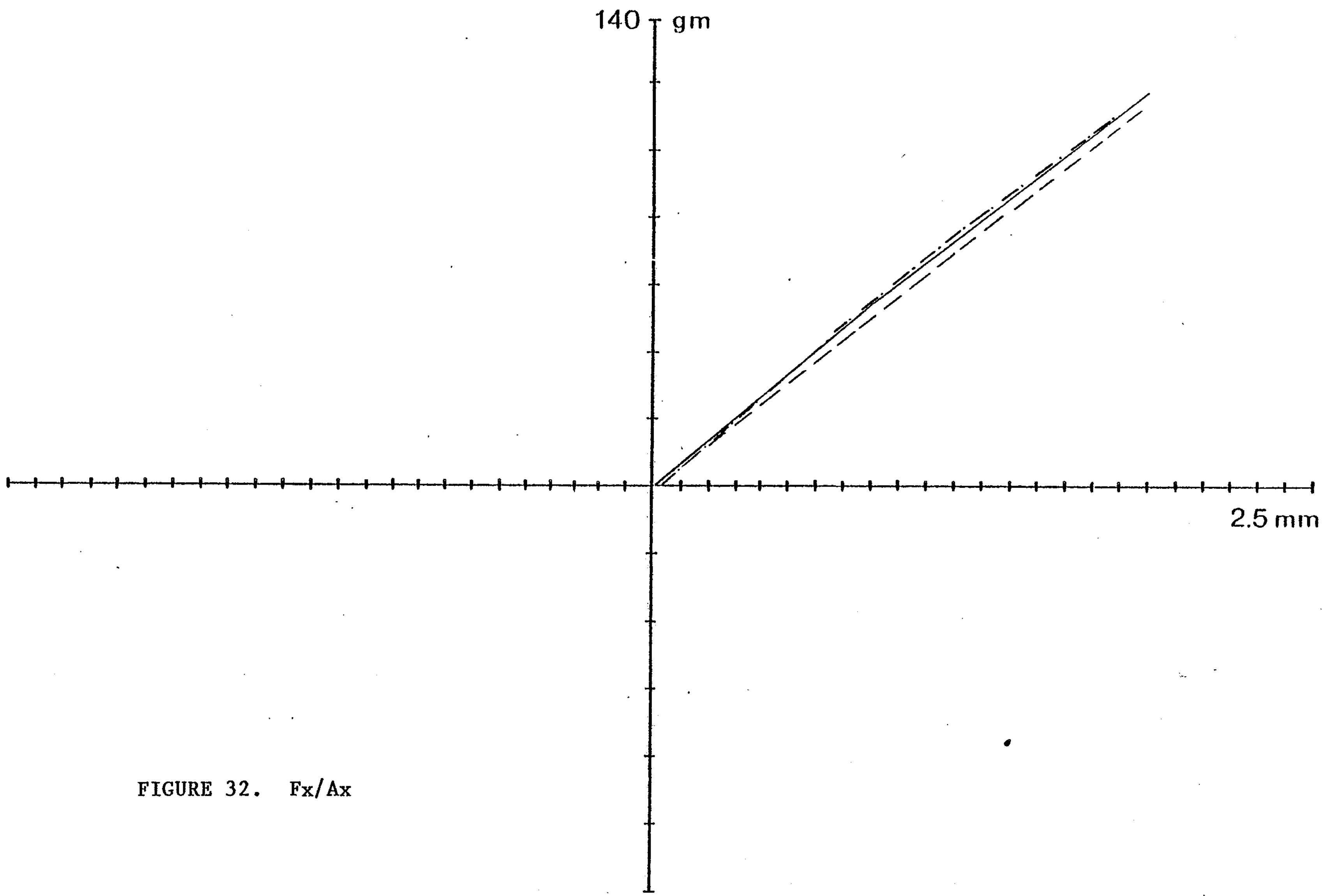


FIGURE 32. Fx/Ax

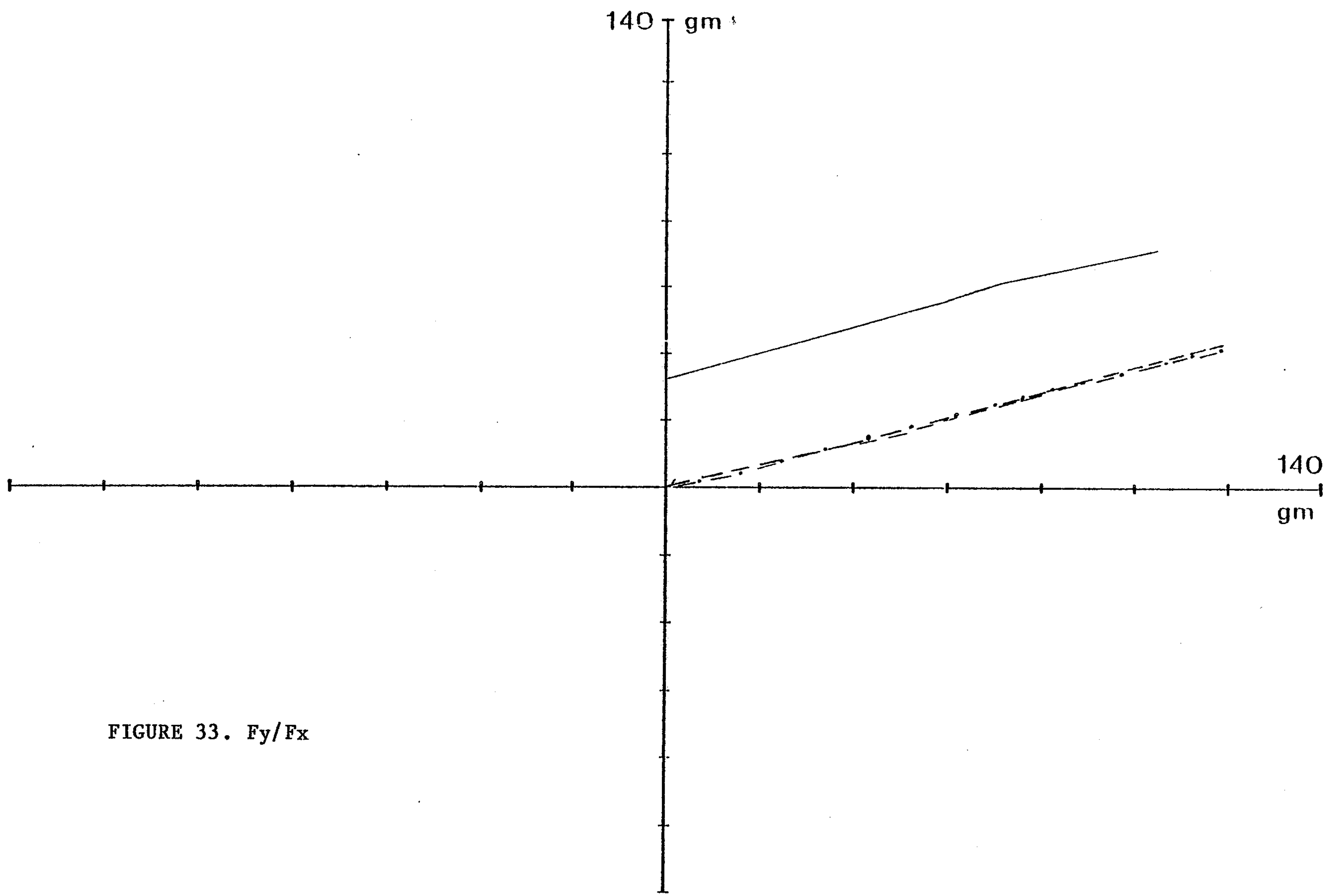


FIGURE 33. Fy/Fx

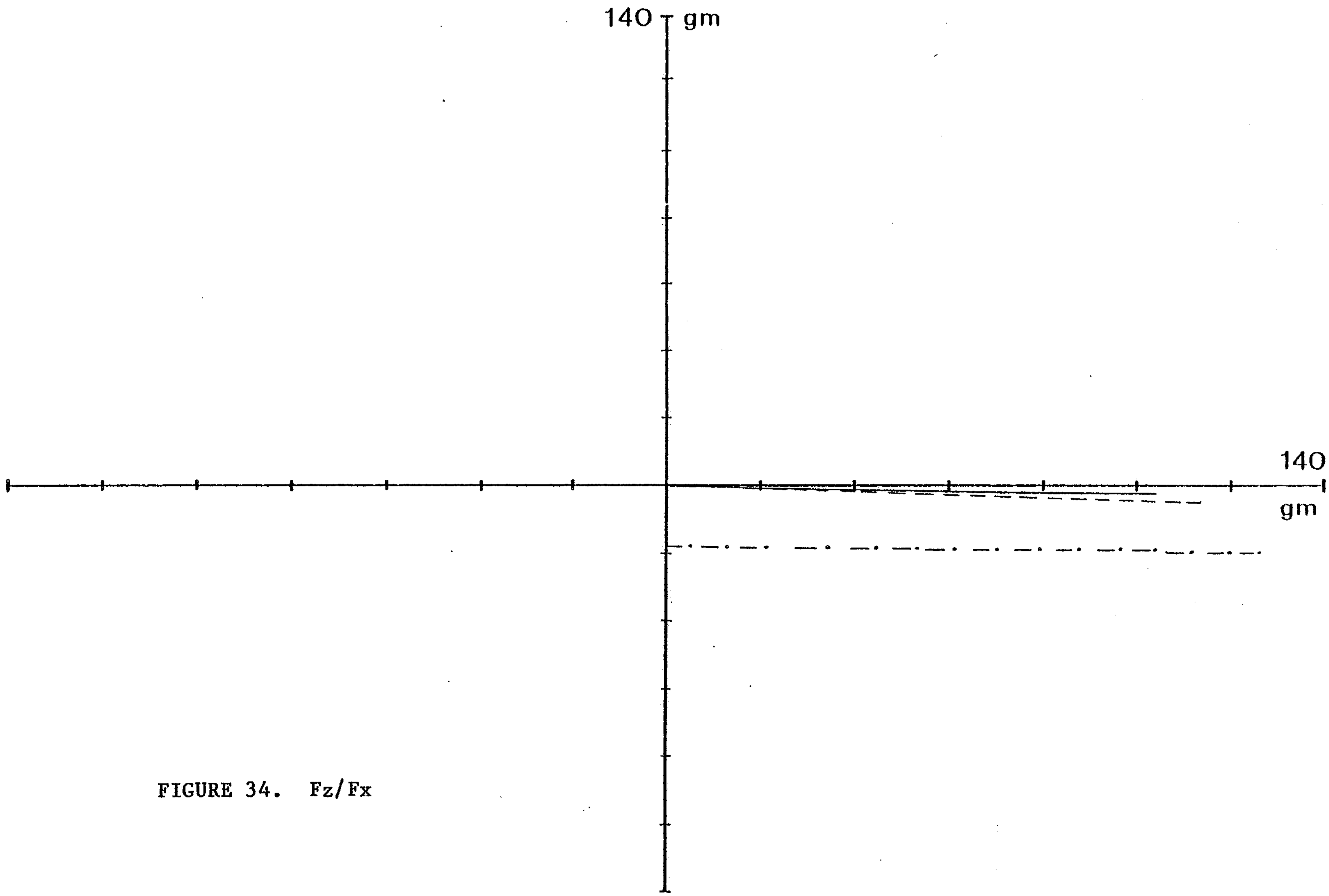


FIGURE 34. Fz/Fx

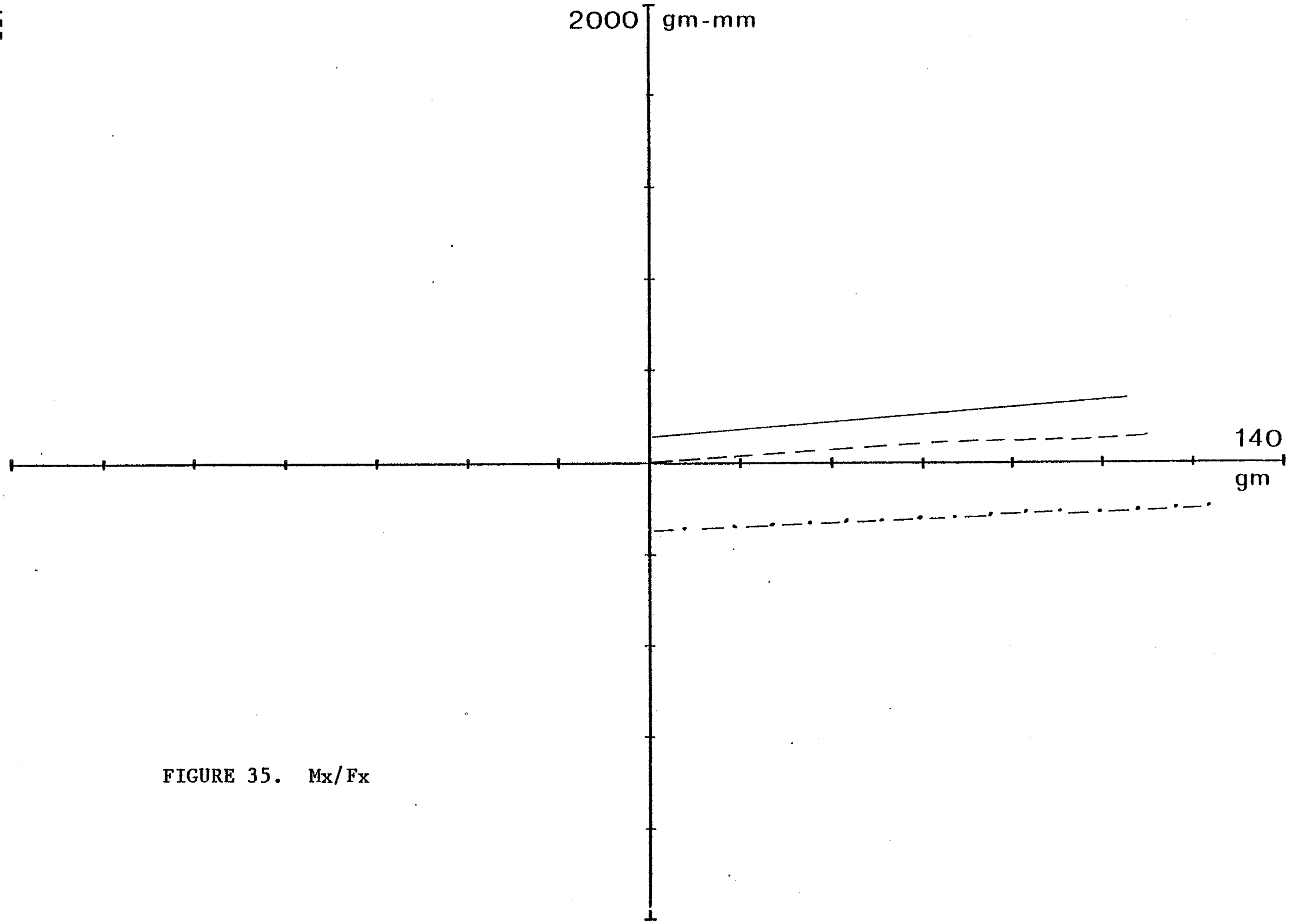


FIGURE 35. Mx/Fx

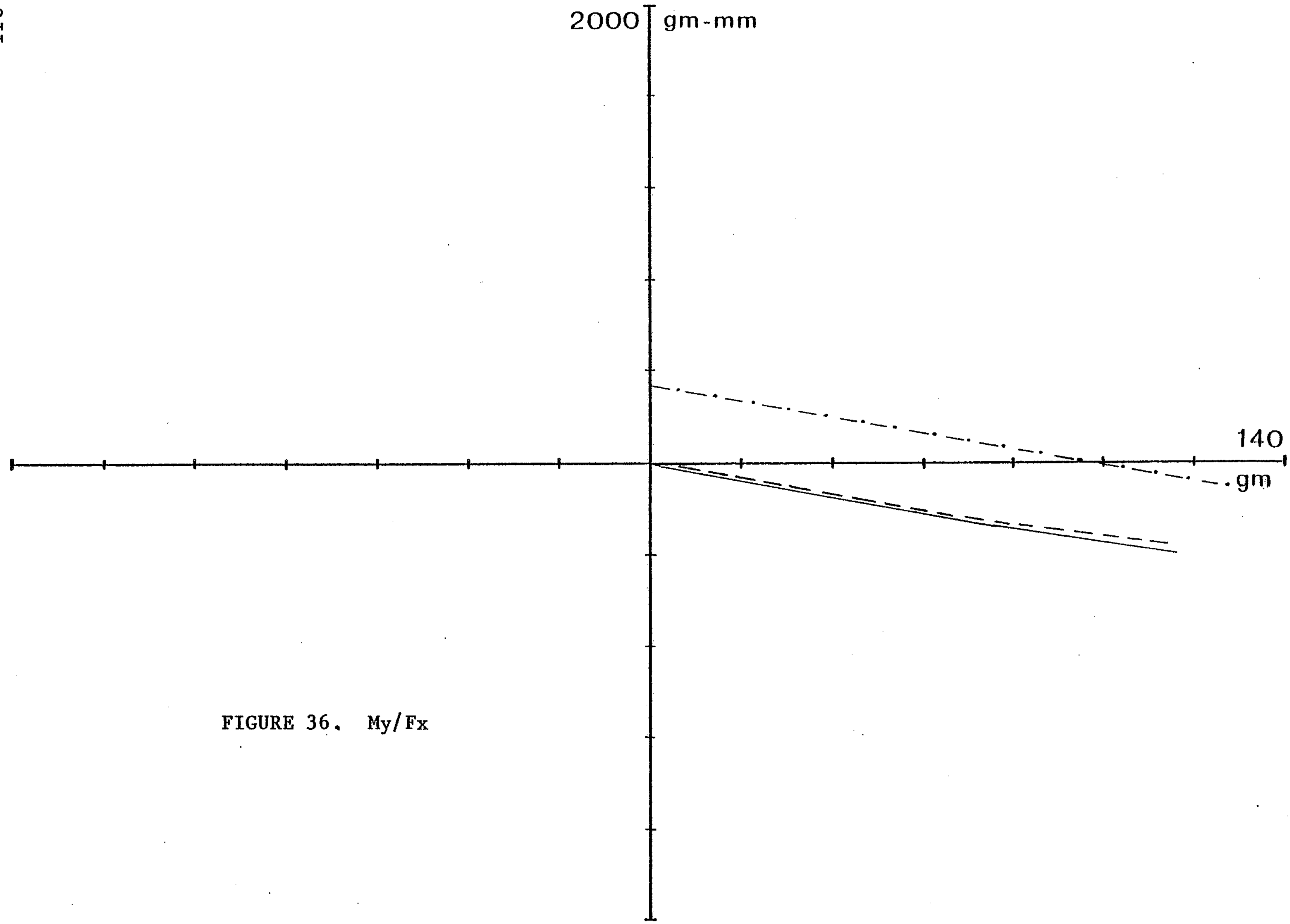


FIGURE 36. My/Fx

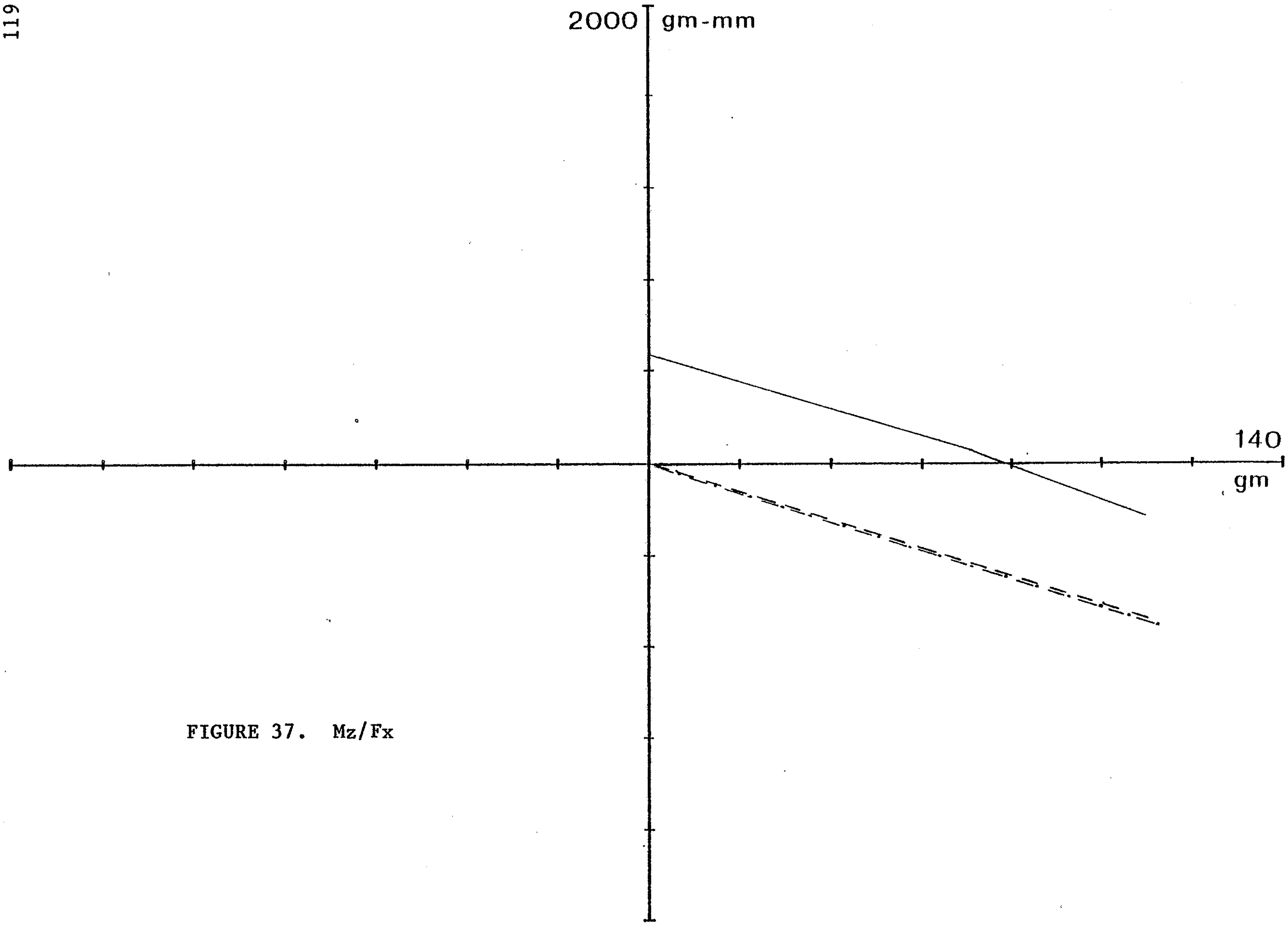


FIGURE 37. Mz/Fx

were also found for the Burstone loop with preactivations.

Table X reveals that the slope characteristics of the loops change little with the incorporation of the gable bends. Changes are observed however in the the V intercepts, implying that with the introduction of gable bends we are introducing a separate force system which functions relatively independantly of the force system that is generated when the loops are activated. The effect of this is to offset but not change the force characteristics of the loops.

The anti-tip gable bend for the vertical loop has the effect of offsetting the Fy/Fx graphs in a positive direction (fig. 33), and producing little effect on the Fx/Ax (fig. 32) and the Fz/Fx (fig. 34) relationship.

The effect on the moments is to produce a small offset of the Mx/Fx (fig. 35) relationship and a larger offset of the Mz/Fx (fig. 37) relationship with no effect on the My/Fx (fig. 36) relationship.

The purpose of the anti-tip gable bend was to reduce the rotation around the z axis as the loop was activated. In reality however what is occuring is that the gable bend together with the effects of the x force sets up a moment around the z axis which varies both in direction and magnitude, so that at only one force level (H intercept) is there a zero moment generated in the z direction. Below this force level, a positive moment is in effect, and above this force level a negative moment occurs.

The anti-rotation bend has little effect on the Fx/Ax (fig. 32) and the Fy/Fx (fig. 33) relationships, but does offset the Fz/Fx (fig.

34) relationship in a negative direction.

The effect on the moments is to offset both the Mx/Fx (fig. 35) relationship (negative V intercept), and the My/Fx (fig. 36) relationship (positive V intercept). There is little effect on the Mz/Fx (fig. 37) relationship.

The purpose of the anti-rotation gable bend is to reduce the rotation around the y axis. As figure 33 demonstrates, the same effects that were seen for the anti-tip gable bend around the z axis are evident for the anti-rotation gable bend around the y axis.

The anti-tip preactivation of the Burstone loop, produced little difference in slope characteristics with x activation. The only effect on the force relationship, is a negative offset of the Fy/Fx relationship , with the other force values exhibiting no changes.

The anti-tip preactivation had little effect on the moment production, with only a slight positive offset present for the Mz/Fx relationship, leading to a similar effect as that found for the anti-tip gable bend of the open vertical loop.

The anti-rotation preactivation produced an offset of the Fz/Fx relationship, with little change in the Fx/Ax and the Fy/Fx relationship. This preactivation also produced a positive offset on both the Mx/Fx and the My/Fx relationship, and a small negative offset on the Mz/Fx relationship.

The anti-rotation preactivation therefore produced the same type of effect on the My/Fx relationship as was seen for the anti-rotation gable bend of the open vertical loop.

The effects of the preactivation on the Burstone loop are not as dramatic as those found in the vertical loop, with the anti-rotation pre-activation of the Burstone loop resulting in much more noticeable effects than the anti-tip preactivation.

Discussion

INTRODUCTION

The present investigation was undertaken to determine the characteristics of selected cuspid retraction loops using instrumentation capable of simultaneously measuring the three-dimensional forces and moments generated by each loop. In any experimental investigation there is an interaction between the techniques employed, and the results obtained. Due to this interaction, the discussion will initially focus on some aspects of the experimental technique and equipment used in investigating cuspid retraction loops. This will be followed by a discussion of the three-dimensional performance of the loops during activation.

EXPERIMENTAL TECHNIQUES AND EQUIPMENT

Theoretical considerations, as well as early experimental results, indicated that the retraction loops to be investigated generate force and moment increments that are closely proportional to the increments in activation generating them. This linearity, therefore, allowed the use of a single number (slope) to represent the relationship between the various pairs of parameters of the loop eg. Mx/Fx.

Two factors can cause a loop to be non-linear. They are, a change in material properties when activation causes stresses to exceed the yield point, and large changes in geometry of the loop as activation is increased.

The yield point of a loop is that activation point that will result in permanent deformation and alteration of the force-deflection rate of the loop. As long as the yield point of the loop is not reached, the force and moment relationships will be repeatable. The yield point for the loop with the most severe force-deflection rate (the open vertical loop) was approximately 2.5 mm. Since the activation distance in the x direction for the vertical loops was 2 mm., the yield point was not reached in any of the loops.

Some small non-linearities were observed in the moment generation of some loops. These could have been caused by lateral buckling which is a geometric effect. They were very small however and were not investigated further.

The data reduction which resulted from the use of slope values was important in view of the large amount of raw data collected. In addition, the six slope values allowed a rapid assessment of the orthodontic performance of a loop as a function of activation, without requiring the digestion of large volumes of data.

The advantages of the simultaneous measurement of data in all three planes were very clear, in that it provided a complete numerical description of the characteristics of a loop at each level of activation. Simultaneous measurement also reduced experimental time and, importantly, ensured that the conditions of activation were identical for the measurement in each plane. By ensuring that the conditions of activation were identical, the error involved in altering the experimental situation, to investigate each force and moment separately, was avoided. Earlier work by Solonche et al. (1976) considered loops to be uniplanar, and therefore, required repeated testing of a loop to investigate all three dimensions. This repeated testing, to compile a complete set of three-dimensional data brings with it the danger of incorporating more experimental error than does simultaneous measuring.

The maximum force level permitted by the measurement system (130 gm.) limited the range of exploration of cuspid retraction loops. This force level also necessitated the use of slightly larger dimensioned loops (10 mm. high), of a smaller diameter wire (.016 in.), than might be clinically applicable. However the primary purpose of the investigation was to examine the force and moment relationships in retraction loops and the available range of exploration was found quite sufficient for this purpose.

In general, the experimental instrumentation proved to be very adequate for the present investigation, exhibiting an accuracy which was felt to be more than sufficient, and which compared well with instruments used by other investigators (Teasley 1963, and Solonche et al. 1976).

PERFORMANCE OF THE SELECTED LOOPS

An ideal cuspid retraction loop, is one that is capable of producing and maintaining the desired force system, necessary to cause the type of cuspid movement wanted. Generally, the most desirable type of cuspid movement in a first bicuspid extraction situation, is pure translation. For the purpose of the present investigation, pure distal translatory movement of the cuspid was taken to be representative of the ideal situation.

For a cuspid retraction loop to be capable of producing pure translation, it would be necessary for it to produce a positive value for Fx/Ax and zero values for the relationships Fy/Fx, Fz/Fx, Mx/Fx, My/Fx, and Mz/Fx as measured at the center of resistance. The extent to which these relative properties deviate from zero would therefore be a measure of how the actual appliance deviates from the ideal.

Many factors are involved in discussing the divergence of a cuspid retraction loop from the ideal. The discussion of the results of the investigation will therefore deal with the following factors in relation to the ideal:

(a) force-deflection rate,

(b) spurious force and moment effects,

(c) moment generation due to geometry,

(d) effects of gable bend preactivations.

FORCE-DEFLECTION.

By definition, the force-deflection rate of any loop is a measure of its stiffness in the direction of activation. Design factors of the loop can influence this force-deflection rate. Reducing the cross-section of the wire, increasing the length of the wire in the loop, and strategic placement of helices can aid in the development of a lower force-deflection rate.

If the results of the Fx/Ax relationship are examined, it will be found that the Burstone loop which possess the largest amount of wire in its design and the smallest section modulus ($.33 \times 10^{-4}$ in. for the Burstone, $.4 \times 10^{-4}$ in. for the round wire), also possesses the lowest force-deflection rate. The vertical loops without helices at their apices possessed the highest force-deflection rates, while the vertical loops with helices and the L-loop were between the extremes. All loops when activated in a positive x direction produced positive values for the Fx/Ax relationship.

Due to the low force-deflection rate of the Burstone loop, a one millimeter closure of the loop will result in a decrease in force magnitude of approximately 18 gm. The open vertical loop without a helix with the same closure will have a decrease in force value of approximately 60 gm. If both loops begin with a given force level of 100 gm. the open vertical loop will lose over one-half this amount per millimeter of closure, while the Burstone loop will only lose approximately one-fifth of this amount per millimeter of closure. From this it becomes obvious that the Burstone loop, with a low force-deflection rate will be able to produce a more constant force level during tooth movement.

In addition to delivering a more constant force during tooth movement, loops with low force-deflection rates offer greater accuracy in control over the desired force magnitude. For example, an error in adjustment of one millimeter in the vertical loop will result in an error in force value of 60 gm. On the other hand, an error in adjustment of one millimeter in the Burstone loop would result in an error in force value of only 18 grams.

SPURIOUS EFFECTS.

The changes in geometry resulting from activation of a loop, produced a number of unexpected forces and moments.

The necessity of having a distally directed force in order to move a tooth to the distal is obvious. As stated above, all loops produced positive values for the Fx/Ax relationship and, as long as the vertical (V) intercept for this relationship is at the origin, any positive Ax will result in a positive or distalizing x force. When the misalignment of the ends of the loop was examined, however, it was found that with a negative y offset it was possible to generate an initial x force in a mesial direction, in addition to the expected negative y force. The slope relationship Fx/Ax remained the same, but the misalignment had the effect of introducing an additional constant force in the x direction (figure 20). The magnitude of this force (for the off-centered closed vertical loop) with a 1 mm. -y misalignment was 18.9 gm., an amount which may be clinically significant.

How the misalignment of the ends of the loop produces a negative (mesial) x force is illustrated in figure 38 (the negative offset depicted is overly large to allow a better visual interpretation). Position A illustrates the situation that exists before the end of the loop is misaligned. Due to the rigid attachment of the ends of the loop to the measuring system, and the asymetric position of the vertical part of the loop, large moments are generated at the loop-mounting tube interface (position B) by a negative offset. These moments have the effect of closing the vertical part of the loop, resulting in an initial negative (mesial) x force. As the loop is activated

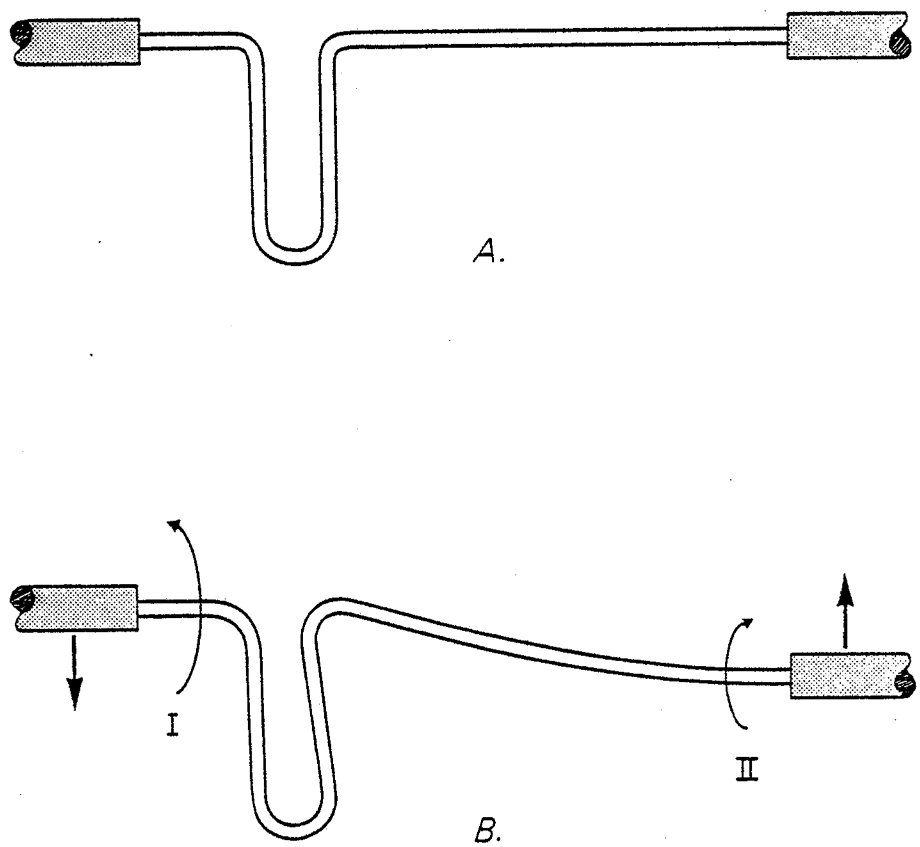


FIGURE 38. EFFECT OF VERTICAL (NEG.) MISALIGNMENT ON THE FORCES AND MOMENTS

positively in the x direction, this negative force has to be counteracted before the desired positive x force is generated. This effect in a clinical situation will significantly alter the effective distalizing activation of a loop, making it far less than ideal. The above effect is reversible with a positive y misalignment producing a positive x force at zero x activation. The above effect on the x force with y misalignment might have been missed had it not been for the comprehensive techniques used in this investigation.

The relative force values for the Fy/Fx relationship, when the vertical portion of the loop is centered, are very small, resulting in almost no force being generated in the y direction by x activation. The only exception to this is the L-loop, which produces an intrusive force when activated. This intrusive force arises due to the asymetric nature of the horizontal portion of the L-loop. The magnitude of the intrusive force is approximately one-third that of the x force. This is a large effect, and is likely to be clinically significant.

Figure 39 illustrates the effects of activation on the centered vertical loops. Position A illustrates the loop prior to x activation. If the ends of the loop were free to rotate, the situation B in figure 39 would arise with x activation. The ends of the loop however are not free to rotate but are constrained in the vertical plane by the measuring instrument. The result of this is to produce moments at the wire-mounting tube interface (position C). Because the loop is centered, symmetrical, and in a state of static equilibrium, these moments will be of equal magnitude but opposite sign and will balance each other, thereby producing no spurious force effects.

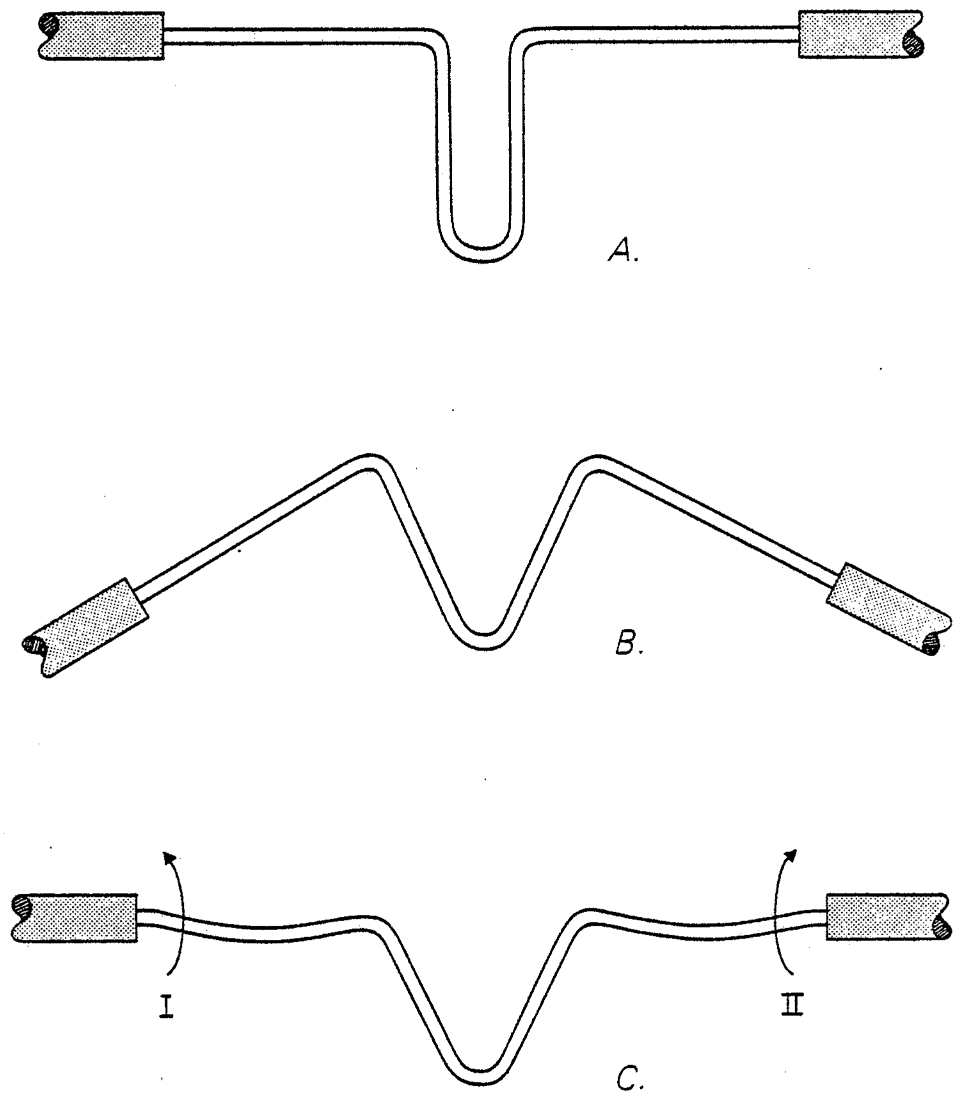


FIGURE 39. DEVELOPMENT OF SPURIOUS MOMENTS (CENTERED LOOP) WITH ACTIVATION (X)

For all the centered loops, the relative force value of the Fz/Fx relationship is also very small.

If these relative values are compared to the values for an ideal cuspid retraction mechanism (zero y and z force), it is apparent that the centered vertical loops (except for the L-loop) generate little spurious y and z forces, thereby providing a y and z force system that is close to the ideal.

When the vertical portion of the loops are changed from being centered, to being 1.5 mm from the model tooth, a spurious extrusive force in the y direction approximately one-third that of the x force arises. This force change also occurs in the L-loop, but in this case the y force becomes much less intrusive. This is an effect that agrees with Burstone's (1976) findings.

The unactivated position of the off-centered loop is shown in position A, figure 40. With activation of the loop, the situation in position B would arise if the ends were free to rotate. Since the ends are constrained, they can not rotate but remain horizontal, resulting in the generation of moments at the mounting tube-loop interface. Because the loop is no longer symetrically placed, the moment that is developed at the mounting tube-loop interface of the shorter horizontal arm, is larger than the moment occurring at the mounting tube-loop interface of the longer horizontal arm (position C, figure 40). The loop however is still in a state of static equilibrium. To balance the moments, therefore, an intrusive force is developed at the end marked II (position C). Since the forces must also be balanced an extrusive force occurs at the end marked I

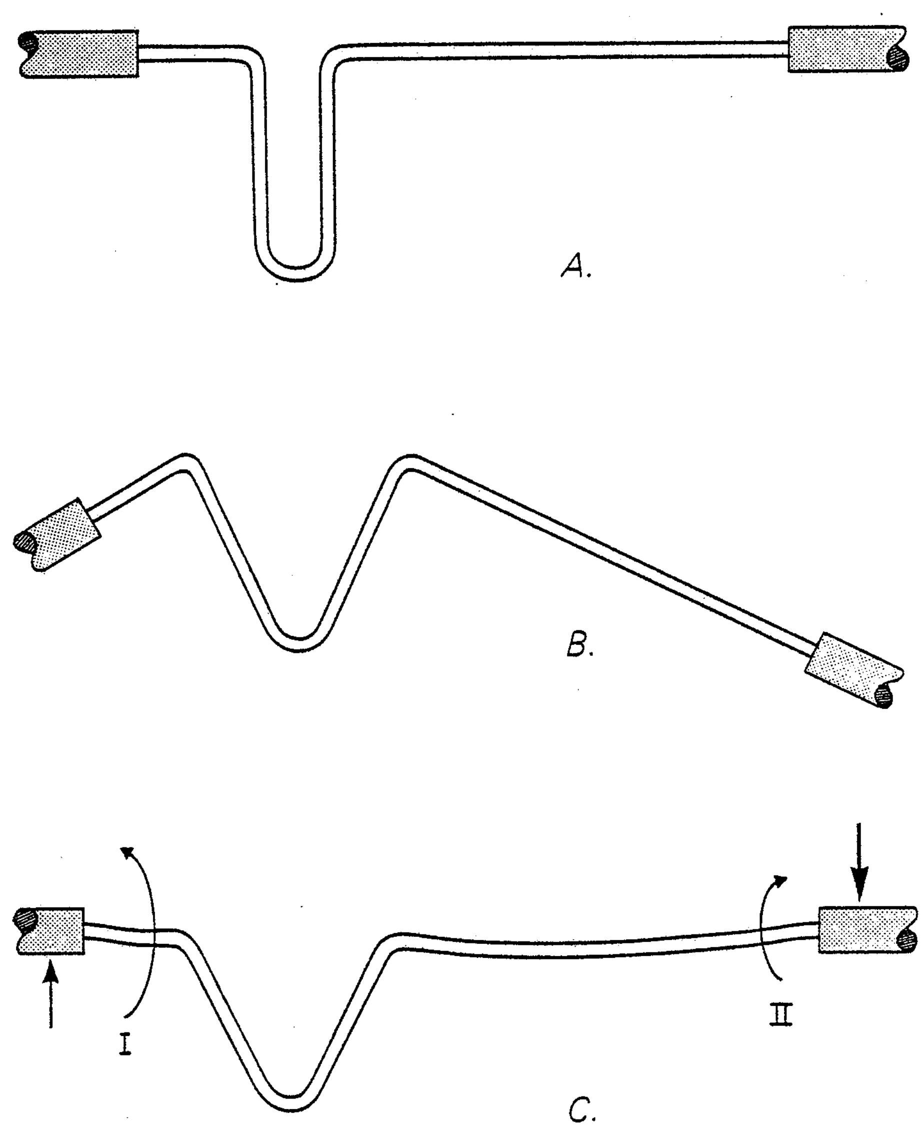


FIGURE 40. DEVELOPMENT OF SPUIOUS FORCES AND MOMENTS (OFF CENTERED LOOP) WITH ACTIVATION (X)

(position C), resulting in the extrusive y force observed.

The force in the z direction does not appear to be effected by the change in the position of the vertical portion of the loop.

If the y and z force systems that arise with the vertical portion of the loop at 1.5 mm. from the model tooth, are compared to the ideal force system, it is found that the spurious y forces, makes this situation less ideal than when the loop is centered. This is true for all the vertical loops except the L-loop, whose performance tends to become closer to the ideal.

The misalignment of the ends of the loops in the vertical plane, produced little change in the Fy/Fx relationship. The misalignment however did produce a second force system whose effects were added to those that arose as a result of the x activation. This additive effect, resulted in a base line value of y force acting even with zero x activation. With activation of the loops, these base line values became simply added to the y force that arises during x activation. The effect on the y force system (figure 21) arose due to the rigid nature of the vertical loops in the vertical plane, so that a small misalignment in the y direction will result in the generation of y forces.

Little effect on the z force is found with a misalignment of the ends.

If this force system is again compared to the ideal, the spurious y forces generated by y misalignment tend to produce a less than ideal situation.

In summary, it has been shown that forces needed to offset moments are in some circumstances very significant and failure to take these into account could produce undesired tooth movement. From this it may be expected that unwanted forces may likewise generate unexpected moments.

The development of spurious moments, and their effects on the force system for the centered loops and loops 1.5 mm. from the model tooth have been dealt with above.

The misalignment of the ends of the loop resulted in an offsetting effect on the moments around the x axis (figure 23) and around the z axis (figure 25). The mathematical calculation of moments in three planes can be accomplished using the following formulae:

$$Mx = yFz - zFy,$$

$$My = zFx - xFz,$$

$$Mz = xFy - yFx.$$

Since the effect of misalignment is to produce an additive effect on the linear Fy/Fx relationship (ie. a positve or negative V offset with zero x activation) it is not surprising that the moments around the x and z axes that depend on Fy in their calculations are affected.

Clinically, therefore, with a misalignment of the ends of the loop, it would be possible to have moments acting around the x and z axes even with zero x force. This is not a desirable clinical situation and could result in rotation and tipping of a cuspid when no movement would be expected.

MOMENT GENERATION DUE TO GEOMETRY.

If a force is applied to an object at a distance away from its center of resistance, the object will experience rotational effects, as well as translatory effects due to this force. In a clinical situation, anatomical limitations make it impractical to apply a force through the center of resistance of a tooth. Therefore, desired tooth movement must be obtained by a force system placed on the crown of the tooth. Since the crown of the tooth is a distance from the center of resistance, the application of a force to the crown, will result in translation and rotation of the tooth.

In the present investigation, all forces and moments were measured at the center of resistance of the model tooth, whose dimensions duplicated those of a cuspid. Since the center of resistance is a distance from the "bracket" of the model tooth, the application of forces to the "bracket" will cause moments around the center of resistance. When translation only is required, these moments represent a deviation from the ideal. Consequently, the performance of a cuspid retraction loop, will depend upon its ability to resist or counteract these moments, with an ideal loop generating zero moments at the center of resistance of the tooth, with the application of a force at the "bracket".

The activation of all loops in a postive x direction, with the vertical portion of the loops centered, and 1.5 mm. from the model tooth, resulted in rotational effects around the three axes.

The moments around the x axis were varied both in terms of direction and magnitude. This suggests that these moments are perhaps due more to random effects such as, small misalignments in the activation system, and lateral buckling of the loops, than to the primary properties of the loops. The slight increase in magnitude of these moments, with the change in the position of the vertical portion of the loop, also indicates that the production of moments around the x axis is relatively insensitive to the position of the vertical portion of the loop. The magnitude of the x moments was on average one third the value of the y moments. This is a small effect and may not be clinically important.

The rotational effects around the y axis were in all cases negative and of similar values. The similarity of the results indicates that the production of y moments is insensitve to the position of the vertical portion of the loop, and arises from the x force acting at a distance along the z axis.

The distance from the long axis of the tooth to the point of application of the force was 4.2 mm. along the z axis. If a force was applied to the tooth by a loop that offered no resistance to rotations around the y axis, the moment generated would be 4.2 gm.-mm./gm.. If the loop offered complete resistance to rotations around the y axis, the moment generated would be zero. The average moment values for the centered and off-centered loops around the y axis was 3.5 gm.-mm./ gm., with a range of from 3.19 to 4.08 gm.-mm./ gm., indicating that the loops offered little resistance to rotation around the y axis. It also indicates that all of the loops tested presented about the same relative stiffness to moments about the y axis.

The moments around the z axis are all negatively directed, and possess the greatest magnitude of all moments generated. These moments arise as a result of the x force acting at a distance along the y axis. The perpendicular distance from the center of resistance of the model tooth to the point of application of the force is 12 mm. along the y axis. A loop that offered no resistance to rotations about the z axis would produce a 12 gm.-mm. moment, while one that offered complete resistance to this rotation would produce a zero moment. The straight, centered, vertical loops, offered about the same resistance to rotation about the z axis. The L-loop, with its horizontal extension, and the Burstone loop were less resistant to this rotation due to their greater flexibility.

The magnitude of the moments around the z axis when the vertical portion of the loop is 1.5 mm. from the model tooth, are approximately two-thirds those found when the vertical portion of the loop is centered. It would therefore appear that with the movement of the vertcial position of the loop, the stiffness around the z axis increases, thereby improving the loop's performance, when compared to the ideal.

Clinically, the moments that arise due to the geometry of the tooth and the need to apply the force system to the crown of the tooth, would result in the tipping of the crown of the tooth to the distal, combined with a rotation of the distal of the crown to the lingual. Placement of the vertical loop closer to the tooth produces a decrease in the tipping of the tooth, but little effect on the rotation.

EFFECTS OF GABLE BEND PREACTIVATION

The incorporation of anti-tip and anti-rotation gable bends was designed to reduce the effects of the moments on the cuspid, thereby producing a more ideal retraction loop (Broussard 1964, Burstone 1966, Remise 1977).

To investigate their effectiveness, two preactivations designed to reduce the rotations around the z axis (anti-tip) and the y axis (anti-rotation), were incorporated into the off-centered open vertical loop, and the Burstone loop. The effect of each preactivation was looked at individually, and compared both graphically, and in tabular form to the forces and moments that arise with no preactivation.

The preactivations were designed to improve on the cuspid retraction ability of the open vertical loop and the Burstone loop. To accomplish this, a reduction in the slope values of the moments that arise during activation should have been found. This did not occur and as can be seen in Table X, there is little change in the value of the slope relatioships. What is evident however is that the gable bends have introduced a separate force system, whose effects are added to the linear effects seen with no preactivations.

The anti-tip gable bend for the open vertical loop, produced little effect on the Fx/Ax relationship (figure 32), and the Fz/Fx relationship (figure 34). It did however introduce a constant force to the Fy/Fx relationship which is indicated by a positive offsetting of this graph (figure 33).

This preactivation also resulted in a positve offsetting of the

Mz/Fx relationship (figure 37), and a small effect on the Mx/Fx relationship (figure 35). No effect was seen on the My/Fx relationship (figure 36).

The anti-rotation gable bend, introduced a force system, that caused a negative offset of the Fz/Fx relationhip (figure 3-21), and little change in the Fx/Ax (figure 3-19), and the Fy/Fx (figure 3-20) relationships. The effect on the moments was to produce a negative offset of the Mx/Fx relationship (figure 35), and a positive offset of the My/Fx relationship (figure 36), with little effect on the Mz/Fx relationhip (figure 37).

The Burstone loop preactivations produced similar additive effects as those given above.

Clinically, the additive effect of the preactivation would be to produce forces and moments that act on the cuspid even with zero x activation. This means, that the zero moment level which would normally occur with zero x force, now occurs at some other level of x force (H intercept) eg. figures 36 and 37. These graphs illustrate an improvement in the performance of the open vertical loop since the loop is now capable of producing zero moments with an x force, which could lead to pure translation. This situation will occur at only one force level. Above this level, the tooth will be rotating in one direction while below this level the rotation will be in the opposite direction. This may produce a "round tripping" effect on the tooth, as the x force changes, which would be an undersirable effect.

Since it is impossible to keep a loop actived at a given value, while a tooth moves, it would be impossible to maintain a situation where the moments around the y and z axes could be kept zero.

Because the values of the moments are smaller around the H intercept, it would indicate that the activation of the loop should not be allowed to vary much from the level required to produce a zero moment. This could perhaps be achieved by the use of a loop with a more constant force-deflection rate (Burstone 1966, 1976) or, perhaps, more frequent reactivation of the retraction loop in an attempt to keep the x force at a given level. The force level of the H intercept for both the y and z moments is between 80-100 grams. If it were possible to maintain this force level during patient treatment, the force system developed would be very close to the ideal and very favourable for translation of the tooth. Of course, a different level of preactivation would yield pure translation at a different value of x force.

SUMMARY.

The three-dimensional, simultaneous, investigation of cuspid retraction loops, provided a complete picture of the forces and moments generated during activation. All loops, as tested, produced numerous undersirable side effects (ie. moments and forces) during activation, with little difference, aside from the force-deflection rates, being found between the loops.

The Burstone loop with the most complicated design, produced the lowest force-deflection rate. The Burstone loop, however, is difficult for the patient to keep clean, and its relatively large dimensions may be a source of irritation. The cost of the loop is also high when compared to the other designs in the study. Due to the large amount of wire in its design, and its flexibility, the loop offers little resistance to the generation of tipping moments. It is, however, more satisfactory when used with preactivation bends.

The open and closed vertical loops are the least complicated in design. They offer more resistance to tipping moments than does the Burstone loop, due to their more rigid nature. This fact however leads to the production of large forces during activation. Due to the simplicity of design, the loops are easy to manufacture and are perhaps less irritating to the patient than more complicated designs.

The loops with helices at their apices, and the L-loop, provided a lower, more constant, force-deflection rate than the plain vertical loops. These loops incorporate more wire into their design than the plain vertical loops, and so are a little more difficult to manufacture. Their resistance to tipping moments was slightly less than the plain vertical loops, but better than the Burstone loop.

No loop as tested was able to fulfil the requirements for an ideal cuspid retraction loop. The incorporation of gable bends to improve the performance of the loops produced an additive effect to the linear relations present but did little to change these relations. The gable bends, due to the introduction of a separate force system, were capable of producing a situation where zero moments could be generated, but this was not a constant effect, occurring at only one x force value. To produce pure translation would require a constant zero value for the moments during the full range of x force. This did not occur with the use of gable bends.

The measurement of three-dimensional moments and forces proved to be a viable undertaking using the instrumentation developed by Paquien (1978). The instrumentation allowed the consideration of an appliance in three planes, not in a single plane as work by Solonche et al. (1976) suggested. The use of this instrumentation in this investigation helped supply concrete, experimental, evidence concerning retraction loops. This can be used to help substantiate or refute claims of individuals concerning their retraction techniques (Burstone 1966, Broussard 1964, Bench 1978), and therefore help supply a better understanding of how cuspid retraction loops function.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The purpose of this investigation was to quantitatively measure the performance in three dimensions of commonly used orthodontic cuspid retraction loops during activation. The measuring instrumentation developed by Paquien (1978) and modified by McLachlan (1979) was used to accomplish this goal. From the analysis of the data, the following conclusions emerged.

(1) The modified measuring instrumentation, provided accurate three-dimensional data on the force and moment characteristics of cuspid retraction loops during activation.

(2) The use of slope relationships, provided an easy means of viewing the results in terms of their orthodontic performance. The use of the slopes was possible due to the straight line relationships that existed between activation and forces and moments.

(3) All loops as tested exhibited behaviour that was far from the translation ideal.

(4) Little difference, aside from the force-deflection rate, was found between the loops.

(5) The incorporation of anti-tip and anti-rotation preactivations introduced a separate, independent force system to that which already existed. This resulted in a shifting of the origin of the effected relations but did not change their slope values.

(6) Vertical misalignment of retraction loops resulted in the

generation of either extrusive or intrusive forces, as well as mesially or distally directed forces, even with no activation of the retraction loop to the distal.

(7) Placement of the vertical portion of the loop closer to the cuspid results in a definite extrusive force arising with distal activation. This does not occur if the vertical portion of the loop is centered.

RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

The results of the present invesigation have led to the following recommendations and suggestions for future research.

(1) An ivestigation into the effects of the cuspid retraction loops on the anchorage units.

(2) An investigation into the effectiveness of an archwire in combating the deleterious effects that arise during loop activation.

(3) An examination of cuspid retraction loops activated in three dimensions.

(4) An examination into the forces and moments generated in the usage of triple control brackets.

(5) An examination into the effectiveness of the "power arm" in producing translation.

(6) An increase in the force and moment range of the measuring instrument to a level required to look at 4 and 5 above.

(7) A refinement of the activation system to allow the carrying out of 3 above.

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Appendix

ACCURACY CHECK OF THE MEASURING INSTRUMENTATION.

An investigation of the modified instrumentation of Paquien (1978) was undertaken to assess the error inherent in the measuring system, the reproducability of measurements taken, and the accuracy of the measurements. This study was carried out after the calibration of the measuring instrument was done by McLachlan (1979).

The investigation utilized a 20mm. long, Elgiloy,* coil spring (.010 in. inside diameter x .025 in. outside diameter). The spring was attached to the measuring system using the procedure outlined in the experimental method.

The data aquisition program (figure 6) was used for the collection of the data, which was stored initially on magnetic computer tape.

An activation distance of 2.5 mm. in the plus x direction was used, as this distance provided a suitable range of force (0-125 grams), to adequately test the instrumentation. Eleven activation points were taken through this 2.5 mm. distance. Prior to the experimental testing, a force of a few grams was placed on the spring to remove any "slop" in the system. A visual inspection of the spring, prior to testing, was done to ensure that the spring was at right

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*Rocky Mountain Orthodontics, Denver, Colorado.

angles to the long axis of the model tooth.

To assess the reproducability of the results, the spring was activated throught the 2.5 mm. distance a total of ten times. Extreme care (using the L.V.D.T. readouts) was taken to insure that each point of activation ie. 0, .25, .5, etc. was the same for each experimental run.

The results of the experiments were collected on magnetic tape, and subsequently placed on a random access computer disc. The use of the disc, facilitated the calculation of the means and standard deviations of the forces and moments acting at each activation point. The means and standard deviations were calculated using a Hewlett- Packard statistical program. Table XI gives these results.

The largest standard deviation in the three forces is plus or minus 1.1 gm. in the x direction with the mean of the standard deviations being +.5 gm.. A standard deviation of plus or minus 1.1 gm. of force is less than 1% of the maximum measurable force value (130 gms.), and was felt to represent a reproducability factor for the forces, that was more than adequate for the experimental investigation of cuspid retraction loops.

The results for the moments, show a maximum standard deviation of plus or minus 20.9 gm.-mm. around the z axis with a mean standard deviation for all the moments of 8.3 gm.-mm. A standard deviation of plus or minus 20.9 gm.-mm. is less than 1% of the maximum measurable moment value (2300 gm.-mm.). It was felt, as for the forces, that a maximum reproducability error of less than 1% was more than adequate

TABLE XI

FORCE AND MOMENT RELATIONSHIPS FOR COIL SPRING.

Ax	Fx		Fy		Fz		Mx		My		Mz	
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
0	+.5	+.5	+0.6	+0.5	+0.0	+0.5	+8.2	+10.8	-2.7	+2.9	+12.6	+7.5
.25	+12.9	+0.8	-0.4	+0.5	-0.5	+0.8	-2.5	+7.2	-58.6	+3.3	-170.4	+14.3
.50	+26.4	+0.6	-1.2	+0.5	-0.2	+0.3	-5.9	+8.8	-110.6	+3.5	-331.3	+10.5
.75	+38.7	+0.7	-2.0	+0.6	-0.7	+0.2	-12.7	+10.8	-160.7	+3.9	-500.0	+20.7
1.00	+50.5	+0.8	-2.6	+0.3	-0.9	+0.4	-19.8	+7.6	-203.8	+3.9	-660.2	+6.2
1.25	+62.2	+0.5	-3.4	+0.4	-1.1	+0.3	-18.7	+7.6	-250.4	+2.5	-814.0	+12.8
1.50	+73.4	+1.1	-3.9	+0.5	-1.4	+0.3	-25.3	+8.6	-299.3	+3.5	-979.1	+14.5
1.75	+85.4	+0.7	-4.8	+0.3	-2.0	+0.6	-32.6	+10.5	-345.2	+2.1	-1138.2	+20.9
2.00	+97.3	+1.1	-5.4	+0.4	-2.4	+0.3	-32.0	+7.7	-400.1	+6.4	-1297.7	+10.3
2.25	+109.1	+0.6	-5.8	+0.3	-2.6	+0.3	-31.6	+11.1	-444.3	+5.2	-1453.6	+8.5
2.50	+120.2	+1.1	-6.4	+0.3	-2.9	+0.3	-27.8	+7.2	-490.0	+5.5	-1613.1	+6.9

for the experimental work.

To assess the accuracy of the measuring instrumentation, the following investigation was carried out. The spring utilized in the above study was subjected to loading by the application of dead weights. A traveling microscope with an accuracy of .01 mm. was used to measure the deflection of the spring. Seven weights with an average weight of 16.9 gms. were added one at a time to a pan attached to one end of the spring, the other end was attached to a ridgid support. The deflection of the end of the coil spring attached to the pan was measured after the application of each weight. This was repeated until all seven weights were added, producing an average load value of 118 gms. This force level was comparable to that found for the cuspid retraction loops in this investigation. The above loading procedure was repeated five times. Table XII gives the mean values for the five experimental activations.

Using a Hewlett- Packard statistical program, the best fit line for the data in Table XII was plotted (figure 41). A best fit line for the data in Table XI of the force in the x direction versus activation was then plotted on the same graph as above. Table XIII gives the correlation coefficients of the plotted values to the best fit line.

A zone of plus or minus 3% of total scale was then constructed around the best fit line for the dead weight measurements. As figure 41 illustrates, all the measured data for the instrument falls within this zone, indicating the accuracy of the measuring device to be within plus or minus 3% of the calculated x force values.

TABLE XII

RESULTS FROM DEAD WEIGHT MEASUREMENTS Fx/Ax.

Ax	Fx
0.38	16.8
0.72	33.6
1.06	50.6
1.45	67.7
1.78	84.1
2.16	101.4
2.49	118.4

TABLE XIII

	Fx	Mx	My	Mz
MEASURED	+.9997	-.8821	-.9998	-.9997
CALCULATED	+.9998	-.8945	-.9998	-.9995

CORRELATION COEFFICIENTS OF PLOTTED VALUES TO BEST FIT STRAIGHT LINE.

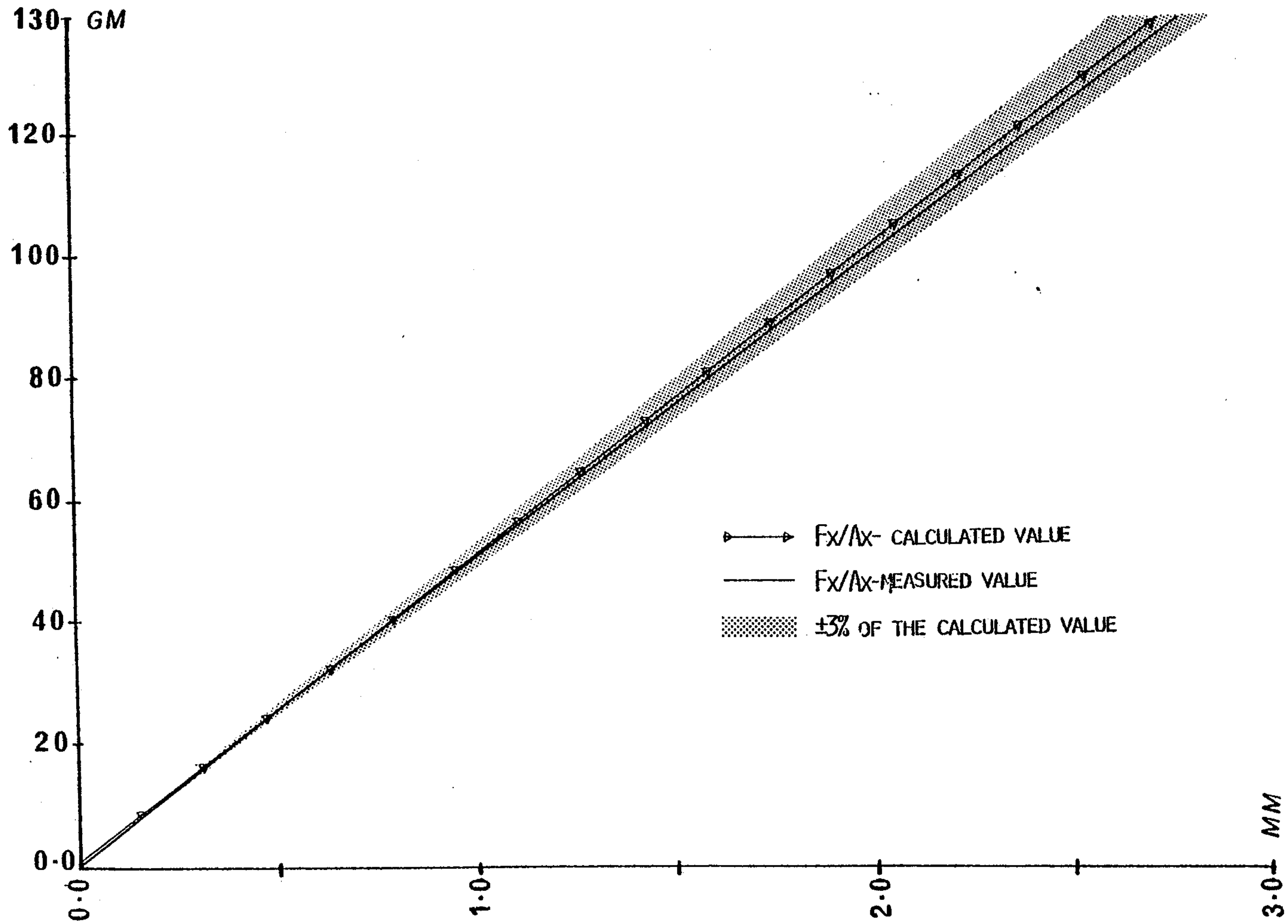

FIGURE 41. Fx/Ax FOR ELGILOY COILED SPRING

The dead weight measurements were used to only assess the accuracy of the force in the x direction, since this was the principal direction of activation in the experimental investigation.

The evaluation of the accuracy for the moments were carried out using the following formula:

$$Mx = y(Fz) - z(Fy)$$

$$My = z(Fx) - x(Fz)$$

$$Mz = x(Fy) - y(Fx).$$

The x distance is the perpendicular distance in the x direction from the long axis of the model tooth to the point of attachment of the spring and was 6.08 mm. The y distance is the perpendicular distance in the y direction from the center of resistance of the model tooth, to the point of attachment of the spring and was 13.24 mm. The z distance is the perpendicular distance in the z direction from the long axis of the model tooth to the point of attachment of the spring and was 4.24 mm.

The values of Fx, Fy and Fz in Table XI were used in the calculation of the Mx, My and Mz moments. The calculation of the three moments was carried out for each point of activation. The best fit line, using the Hewlett- Packard statistics program, was then plotted for the calculated and measured values (Table XI) of the three moments. A zone of plus or minus 3% of the total moment scale was then constructed around the calculated value curves. Figures 42, 43, and 44 illustrate the results of this graphing. Table XIII gives the correlation coefficients of the plotted values to the best fit line. It can be seen from the above figures, that all the measured data will

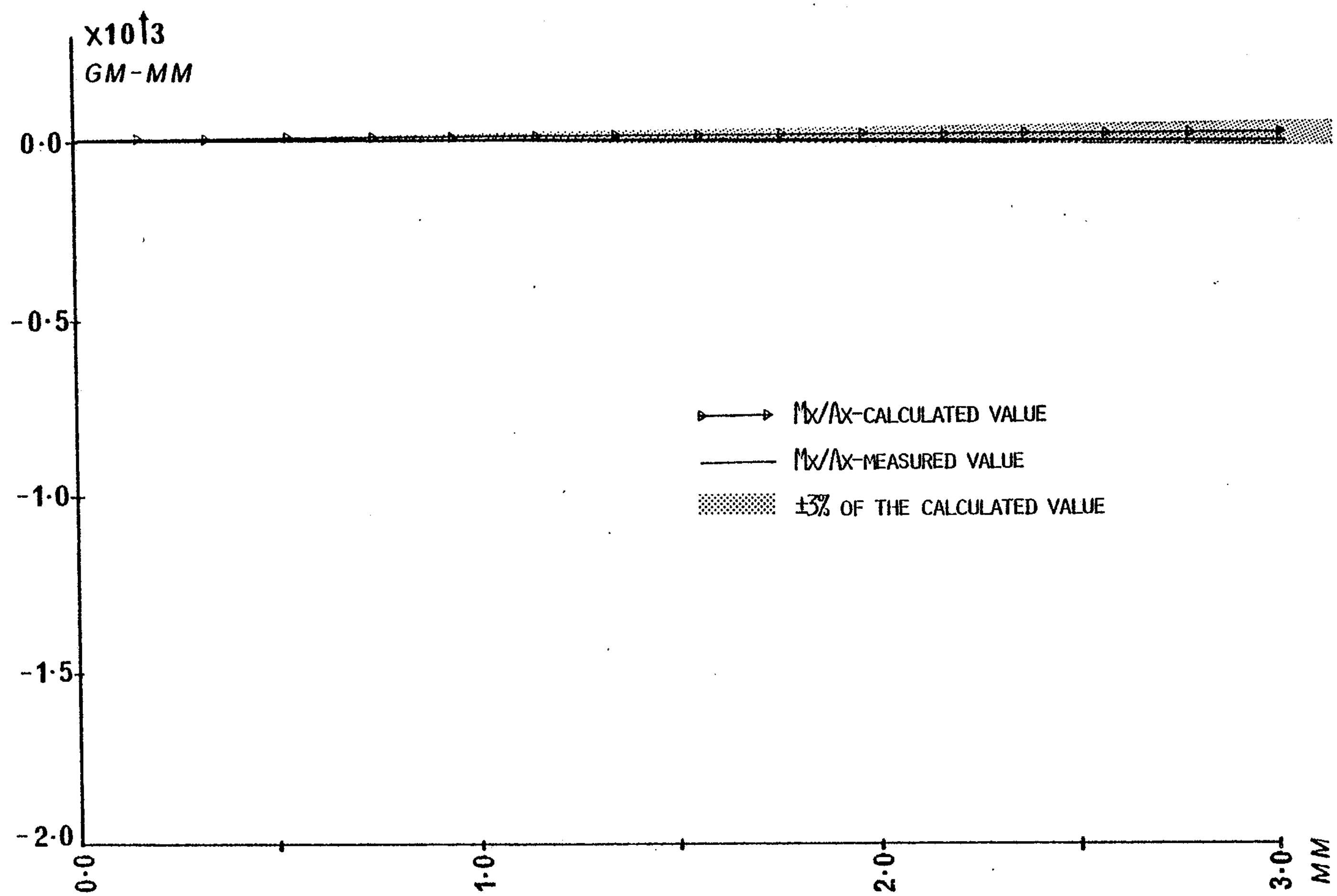

FIGURE 42. Mx/Ax FOR ELGILOY COILED SPRING

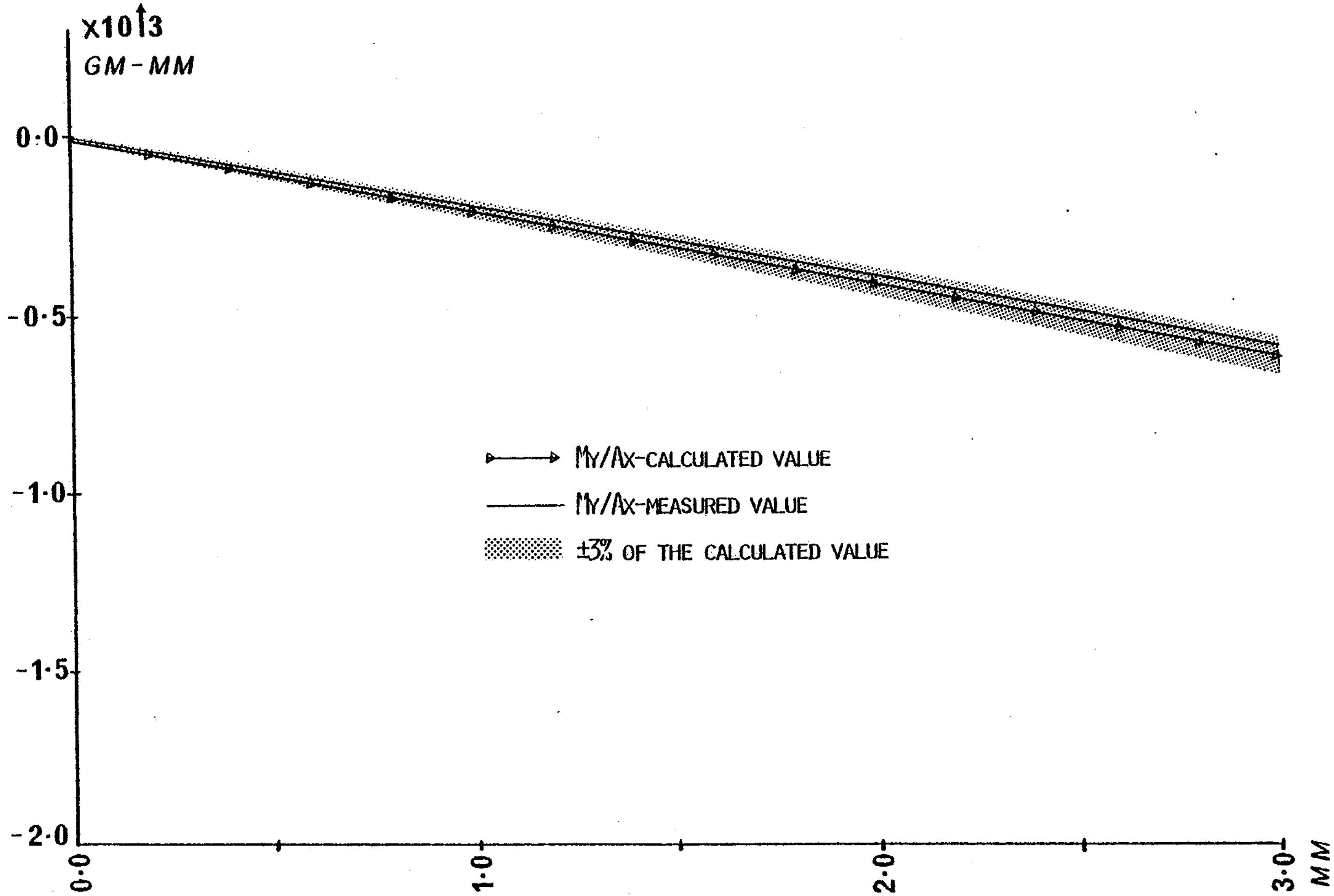

FIGURE 43. My/Ax FOR ELGILOY COILED SPRING

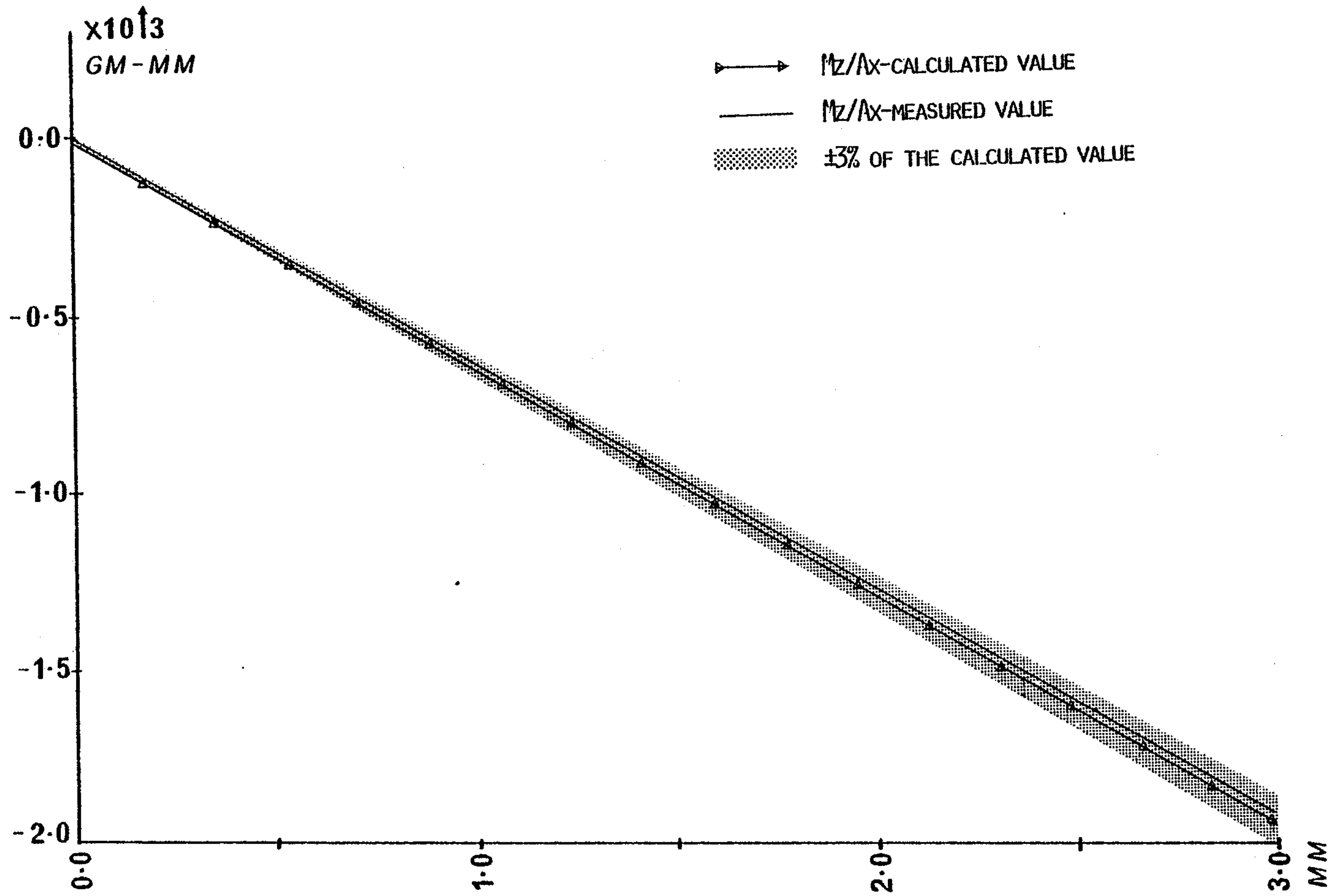

FIGURE 44. Mz/Ax FOR ELGILOY COILED SPRING

fall within the plus or minus 3% zone of the calculated values. This accuracy of the measuring device, for moments, was deemed acceptable for the experimental work.