An Investigation of Intramaxillary Anchorage with Low Modulus Archwires

by

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A thesis
presented to the University of Manitoba
in partial fulfillment of the
requirements for the degree of
Masters of Science
in
Preventive Dental Science

Winnipeg, Manitoba
November, 1985

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ABSTRACT

The practice of fixed multi-band orthodontics today relies in large measure on the use of continuous low modulus archwires for inital alignment procedures.

A previous study at the University of Manitoba examined the forces and moments generated on malposed teeth when these wires are employed in typical straightwire situations. The present investigation is an extension of this earlier work and examines these wires in their capacity to provide anchorage for teeth adjacent to malaligned teeth. The anchorage capacity of rectangular stainless steel wire was also examined, and hence comparison between the wire types was possible.

A measuring instrument developed at the University of Manitoba designed to simultaneously measure three dimensional forces and moments was used to generate the data. The apparatus was modified to allow for rotational displacements, which previously had not been possible. Results were obtained using commercially available wires in conjunction with selected geometric and ligation variables. The results obtained suggest the following:

1. When using flexible wires for initial alignment, significant rotation and tipping of the tooth next to a malaligned tooth will occur.

2. Frictional forces will prevent mesial-distal 'jiggling' of the first in line anchor tooth when it is coupled to a buccally displaced tooth. When coupled to a tooth in lingual version, friction is greatly reduced and 'jiggling' likely occurs.
3. Rotational anchorage with rectangular wire is not as rigid as expected. Deformation of the ligature will occur when the rectangular wire makes forceful contact with it. The likely result is a lack of complete wire engagement, leading to differences in second and third order orientation between neighboring teeth.
4. Ligature deformation appears to be due to, the rectangular wire exceeding the bending stiffness of the ligature, as well as the sharp edge of the wire 'gouging' the ligature surface. As such, employing a larger ligature, helped decrease deformation by 60%.
5. Tying the ligature on the side of the bracket where the wire will contact it, does not improve the ligature's resistance to deformation, despite the fact that the ligature contains more wire on the tied side.
6. When using a figure-of-eight ligature tie to connect teeth in the anchor segment, the archwire contributes nothing to the anchorage capacity.
7. Placing a figure-of-eight tie on the side of the anchor segent where teeth tend to rotate toward each other, causes the ligature to loosen. The result is essentially a zero increase in anchorage, regardless of the wire connecting the teeth.

8. Tying the figure-of-eight such that movement within the anchor segent places a tensile stress on the ligature results in substantial increase in anchorage capacity, regardless of the wire in the brackets.

9. Analysis of the expected reactive movement within an anchor segent will in some instances require that lingual attachments be placed in order to ensure placing the correct stress on the figure-of-eight tie.

10. Unfortunately, the initial tension produced when securing the figure-of-eight tie, produces a force which tends to loosen the ligature, thereby potentially decreasing its effectiveness to augment anchorage.

DEDICATION

FOR LYNN

Who made this accomplishment possible, and without whom it would not have been worthwhile.

ACKNOWLEDGEMENTS

The preperation of this thesis represents the efforts of a number of talented and generous people whose contributions I most gratefully acknowledge.

Firstly, I would like to thank my research advisor Dr. Ken McLachlan, who in his capacity as mentor provided me with inspiration, advise, and above all with friendship, which I hope will always endure.

I would also like to thank my committee members, Dr. George Bowden; for graciously consenting to review my manuscript, and for his sincere suggestions, and Dr. Arthur Storey; whose standards of excellence were both a challenge and an honor to meet.

Sincere appreciation is extended to Dr. Dan Pollit, whose photographic expertise was invaluable in preparing the color prints included in this thesis.

I am indebted to Dr. Keith Levin, whose design work enabled me to virtually step in and begin working. And Mr. H.J. Clark, of the Civil Engineering Workshop, for his always prompt accomodation of my usually impromptu requests.

I would like to thank my classmates, Dr. Ivan Dario Jimenez, and Dr. M. Faisal Talass, for the interest and the support they have shown me during our time together. I wish them happiness and good fortune in the future and remind them to always 'RELAX GUYS'.

Finally, I thank my parents, whose confidence in me, and sacrifices for me, made possible my education.

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Chapter I

INTRODUCTION

The objective of orthodontic force application is tooth movement. The diagnostic process is performed to evaluate among other things malposition of individual as well as quadrants of teeth. Treatment planning subsequently determines which teeth are to be moved (or not moved) to achieve the generally accepted goals of optimum esthetics, function and stability. The degree to which we are able to control tooth movement then, may be used as a criterion by which treatment success may be evaluated.

Throughout the history of orthodontics, researchers have worked to provide techniques and materials by which tooth movement may be achieved in the most effective and efficient manner. Recent metallurgic research has resulted in the development of the so called low modulus archwires. These wires are promoted for their flexibility which enables them to engage malaligned teeth without loop placement. A recent investigation done at the University of Manitoba raised many questions concerning the biocompatibility of these wires. Chief among these was concern about their ability to prevent unwanted movement of adjacent teeth, which act as "anchors" for the malaligned tooth. To date, little research exists evaluating their anchorage-providing capacity. It is for this reason that this study has been initiated. By utilizing instrumentation developed at the University of Manitoba, a three-dimensional analysis of anchorage preservation with low modulus archwires was undertaken. Their performance in this regard will be discussed.

Chapter II

REVIEW OF LITERATURE

2.1 INTRODUCTION

When considering anchorage,it is necessary to focus on three areas of concern. First, the degree to which anchor teeth are subject to spurious forces as a result of force application to the teeth we wish to move. Second, The magnitude of the spurious forces relative to that thought necessary to generate tooth movement within the anchor segent. And third, how the coupling of teeth with an archwire prevents movement wwithin the anchor segment.

It is within this convenient framework that the literature review will be considered.

1. Force Systems in Continuous Arch Therapy - examines the character and magnitude of the forces generated upon malposed as well as adjacent (anchor) teeth, when coupled by continuous arches.
2. Force Levels and Tooth Movement - reviews the force levels thought necessary to initiate and sustain tooth movement.
3. Anchorage Modalities - reviews the generally accepted modes of anchorage preservation.

The purpose of this review is to establish the basis on which a quantitative analysis of anchorage characteristics with flexible archwire should be undertaken.

2.2 FORCE SYSTEMS IN CONTINUOUS ARCH THERAPY

Steiner (1932) was among the first to describe the force systems present with continuous arches. He reasoned that when all teeth are passively ligated to a round archwire except for lingually displaced central incisors, engagement of the centrals will cause each lateral incisor to act as a fulcrum of a lever causing lingual displacement and mesial rotation. As the laterals move a buccal displacement and distal rotatory force is exerted on each cuspid, which in turn exerts the opposite effect on the first bicuspid. Steiner felt this ripple effect continued its way down the arch jiggling the teeth into their final positions.

Richmond (1933) provided some quantitative evidence to this effect in an in-vitro experiment that he performed. Using a strain gauge of his own design he expanded a conventional ribbon arch so as to deliver six ounces (170.1 g) of buccal pressure to simulated maxillary first molars. However, after applying 15 ounces of pressure to ligate a lingually displaced premolar, he found the force on the molar had been changed to 8 ounces (226.8) in a lingual direction.

Drenker (1956) performed a mathematical analysis of the forces and torques associated with second order bends for a four tooth buccal segent. His calculation yielded the following results:

1. In any archwire with second order bends, the torques created are balanced by a couple which intrudes teeth at one end of the segent, and extrudes them at the other end. The direction of the couple is always opposite to the sense of the torques.

2. The torque received by either end tooth is approximately one-half of that taken by any one of the other teeth in the segent.
3. Extrusive and intrusive forces as high as two pounds and torques as high as 0.5 pound-inch (56.5 g-mm.) can act on teeth immediately following placement of the wire.
4. A wire with a lower modulus of elasticity than stainless steel would exert a milder effect on the dentition.

Burstone (1962) stated that with continuous arch wires adjacent teeth are automatically selected as anchor teeth for a given type of movement. Using cuspid root uprighting as an example, he states that anterior extrusion and bicuspid intrusion are unavoidable side effects with continuous arches. Furthermore, these negative effects are increased with continuous arch wires that have

1. smaller cross-sections
2. a great deal of play between wire and bracket, and
3. added flexibility produced by loops or other wire configurations.

As an alternative Burstone (1966) outlined the segented arch technique in which anchor teeth could be selected regardless of their position in the arch. In addition it allowed for:

1. the use of multiple cross-sections of wire simultaneously
2. increasing interbracket distance and subsequent force levels
3. non-continuous force distribution
4. minimal arch fabrication and

5. force calibration of active components

all of which predispose to greater control over force magnitude and direction.

Simms in 1972 reassessed the use of multi-looped continuous arches which increased in use following the introduction of the Begg (1956) technique. He noted that the addition of loops offered advantages. For example, force levels on individual teeth could be reduced, and improved resiliency of the wire between brackets could be achieved. However, he demonstrated that intra-oral anchorage control was greatly diminished with excessively looped arches because they introduced a number of reciprocal complications. He recommended a return to uncomplicated round arch forms, which employed a minimum of loop inclusions as this was more representative of true Begg technique and avoided uncontrolled tooth movement.

In 1974, Burstone and Keonig described a method to analyze the forces generated from an ideal continuous archwire. They approached the problem by describing six classes of two tooth geometries, which were analyzed by a computer program based on linear beam theory involving one plane of space. They proposed that by laying a length of straight wire between two brackets and analyzing the angle and distance between them, one could clinically determine the forces and moments acting on the teeth (in one plane of space). Presumably, by summing a series of two tooth segents around the arch, the force systems acting on all teeth could be determined. Though logically sound the system is clinically impractical and incomplete as three dimensional information is lacking. Its greatest merit lies in its description of the force characteristics of various two tooth arrangements and its demonstration of the indeterminancy that is encountered with continuous arch wires.

Shrody (1974) examined in-vitro the buccal segent reaction when anterior teeth were lingually torqued, five, fifteen, and twenty-five degrees. Using an apparatus specifically designed for the study and simulated plexiglass canine, pre-molar and molar teeth, three dimensional evaluation of

1. counter-torque,
2. occlusogingival and,
3. buccolingual displacement

was investigated. He reported the following results

1. Countertorque force ranged from a minimal value of 320 g-mm. to 4500 g-mm and was the major reactive force component.
2. An intrusive force was placed on the buccal segent teeth with forces as high as 217 g on the canines and decreasing progressively from premolar to molar.
3. All wires at each activation demonstrated a contractile force in the canine region diminishing rapidly at the premolar and molar where even slight expansion forces occurred.
4. Due to the heavy forces, progressive torque should be used whenever possible for more equitable reactive force distribution.

Waters (1976a,1976b) and Waters et. al. (1975a, 1975b, 1981) wrote a series of articles in which the mechanics of plain and looped archwires were analyzed. Both single and multi-stranded arches were examined. In order to make the analysis feasible the following simplifying assumptions were made:

1. archwires contact the brackets at single points only.
2. The rotational forces generated by the use of wide brackets would not be analyzed.
3. The distance between brackets on adjacent teeth are equal.
4. All loads are centrally applied.

Using these assumptions in combination with linear beam theory, some of the conclusions the authors reached include the following:

1. The force applied to a misaligned tooth is directly proportional to wire parameters E (Young's Modulus) and I (second moment of area), and to the distance the wire has been displaced from its normal position.
2. If a misaligned tooth is to be displaced lingually, alternate lingual and labial forces of decreasing magnitude are applied at successive restraints.
3. Any light wire has the disadvantage in that it cannot resist unwanted extrinsic forces. The flexibility which allows initial alignment of irregular teeth, poses problems for control of molar position particularly when intermaxillary elastics are used.

In addition it was calculated that when the defined span length is kept constant at 13 mm, changing from a point contact bracket to a 3 mm wide siamese bracket, increased the stiffness of the span 6.4 times.

These and other examinations (Burstone et. al., 1973) were all hampered by the necessity of making the mathematical analysis feasible and as such many simplifying assumptions similar to those made by Waters etc. were required (Burstone and Keonig, 1974, Waters et. al. 1975a,1975b). In addition, only one and two dimensional data was produced.

In 1982, Sullivan using a specially developed apparatus was able to measure in three-dimensions the forces and moments generated by standardized light wires. An important finding of his study was that with a continuous low-modulus archwire, forces and moments comparable with those generated on a buccally or lingually malaligned tooth are generated on the first in line anchor tooth. The extent to which these teeth are susceptible to these forces was not discerned, however, he considered it to be significant to the point of suggesting control over final tooth position was impossible.

It would appear from the above review that considerable evidence supports the view that teeth adjacent to malaligned teeth are subject to significant reciprocal forces. In many instances, movement of these teeth is undesirable, as they are already aligned and ideally, should provide anchorage for the malposed tooth or teeth. Sullivan's (1982) work showed that in situations typical of those encountered clinically, that forces ranging from 600 to 1050 grams are exerted on a buccally or lingually malaligned tooth. However nearly equal and opposite forces and moments are exerted on the first tooth in the anchor segent.

In order to consider these forces appropriately it is necessary to analyze them within the context of force levels thought necessary to produce tooth movement. Thus, potential anchor tooth movement can be more fully evaluated.

2.3 FORCE SYSTEMS AND TOOTH MOVEMENT

It may be stated that the objective of force application in orthodontics is tooth movement in accordance with treatment objectives. The force with which this goal is most efficiently obtained may be considered the optimal force system. However, universal agreement as to what constitutes this optimal force system does not exist even today. In the past it has generally been defined as that force which produces:

1. a rapid rate of tooth movement
2. a maximum biologic response
3. a minimal damage to oral tissues
4. minimal patient discomfort.

(Smith & Storey, 1952; Storey & Smith 1952; Burstone 1962; Hixon et. al. 1969; Jarabak & Fizzel, 1972; Gianelly & Goldman, 1971.)

Most recently Burstone (1985) has submitted that an optimal force system is one that:

1. accurately controls the centre of rotation of a tooth during tooth movement.
2. produces optimal stress levels in the periodontal ligament
3. maintains a relatively constant stress level as the tooth moves from one position to the next.

Much of the research in this area has been directed towards establishing standardized numerical force levels which when applied, produce the above-stated objectives. The following is a review of the important developments in this area.

2.3.1 Ideal Forces

Richmond in 1933 noted that investigators in the mid-eighteenth century cautioned against the use of excessive forces which slowed tooth movement, as well as new bone development. He recommended that forces applied to teeth need not exceed 16 ounces (453.6 grams) as those were more "physiologic" and less apt to cause biologic damage.

Schwartz (1932) using an animal model sought a force that would move teeth through bone, while maintaining the integrity of the periodontium. He applied a type of fixed multi-banded appliance to a dog and subsequently evaluated the teeth and the periodontium histologically. It should be pointed out that Swartz did not actually measure the the forces on the teeth, rather he estimated what he thought they were. He concluded that the most favorable tooth movement could be achieved when forces did not exceed the pressure in the blood capillaries, 15 to 20 millimeters of Hg or approximately 20 grams of force per square centimeter of root surface. He subsequently categorized force levels into four groups based on their biologic effect:

1. a force of short duration with no apparent tissue reaction
2. gentle forces of 20-26 grams per square centimeter of root surface, yielding no root resorption.
3. moderately strong forces causing regressed blood flow with accompanying root resorption, and,
4. strong forces causing undermining resorption.

Oppenhiem in 1936 and again in 1944 recommended the use of very light intermittent forces. He felt forces exceeding 240 grams (8 ounces) were pathologic.

Stuteville in 1938 reviewed the literature and research related to tissue changes incident to tooth movement. He recommended that there were three relevant factors to consider in orthodontic force application:

1. the amount of force delivered,
2. the distance through which the force acts,
3. the muscle forces involved.

He advocated forces in the 150 to 200 gram range for desired tooth movement.

Schwartz's (1932) recommendations, though not universally supported, e.g. Paulich (1939), were accepted (Strang, 1943, Moyers and Bauer, 1950, and Halderson et. al., 1953) and remained as guidelines for the orthodontic community for approximately 20 years.

In 1952 Smith & Storey performed their oft quoted study which examined the rate of tooth movement as a function of the magnitude of applied force. Using a sample of five patients, ranging in age from 12 to 15 years, in which mandibular first premolars had been extracted, the first molar, second bicuspid and cuspid were banded and served as the anchor unit. The left cuspids were individually retracted with springs producing 400 to 600 grams. Lighter forces were used for retraction on the right side, leading them to suggest that forces of 150 to 200 grams produced optimal cuspid movement. Forces above this range resulted, not only in less cuspid movement, but anchorage loss as well.

Around the time Smith and Storey (1952) published their work, Reitan (1951,1957) began his now classic investigation on the histologic response of the tooth and periodontium to orthodontic force application. His description of compressed areas within the periodontal membrane, which he termed hyalinized zones, were intimately related to the amount of force applied and the subsequent tooth movement that resulted. Large forces resulted in longer durations of hyalinization (as long as 23 days) during which no tooth movement occurred. Undermining resorption was required before osteoclasts could reach the tooth-bone interface to expedite frontal resorption. Although varying forces are indicated as ideal for certain movements based on histological criteria, Reitan (1957) advocates applying a light initial force to increase cellular activity without causing undue tissue compression and to prepare the tissues for further changes.

For example 25 to 30 grams is preferable for intrusion of teeth, with an even lesser force recommended for extrusion. Tipping of incisors and premolars is optimal with 50 to 70 grams, while movement of smaller teeth is most favorably done with 20 to 30 grams.

Begg (1956) based on clinical experience suggested that individual cuspids as well as en masse anterior retraction could be accomplished with forces slightly less than those recommended by Storey and Smith (1952).

Burstone and Groves (1960) found that retraction of anterior teeth by simple tipping was best accomplished with forces in the vicinity of 50 to 70 grams, which correlates with Reitan's (1957) recommendations. Increasing forces beyond this level did not result in more efficient tooth movement.

Emphasizing that force control was important, Stoner (1960) based on empirical evidence suggested applying a continuous force in the range of 2 to 6 ounces (56.7 to 170.1 grams).

In 1963 Newman analyzed the Begg technique from a biomechanical perspective. He concluded that all tooth movement could be accomplished using one to four ounces (28.4 to 113.4 grams) of force.

In 1967 Weinstein conducted an experiment in which resting buccinator muscle pressure was measured. Gold onlays were fabricated for premolars, so as to extend 2 mm buccally beyond normal anatomic form. A buccal musculature force of 1.68 grams was calculated, which produced one millimeter of movement over eight weeks.

Andreason and Johnson (1967) studied the effects of differential force application on sixteen patients. Employing an asymmetric cervical headgear in which 200 grams was applied on one side, and 400 grams to the other, they found that the higher force produced a greater rate of tooth movement.

Ackerman et. al. (1969), in accordance with Reitan (1957) suggested that there was no single optimum force to produce desired tooth movement. Rather, a broad range of forces could produce similar results depending on the duration over which they were applied.

Hixon et. al. (1969) attempted to determine the optimum force necessary to bodily retract canines. However they were prevented due to inability to control rotation and tipping. Nevertheless their study led them to conclude that with 300 grams of force, the average rate of tooth movement increased as the load per unit area of periodontal ligament increased. They felt there was insufficient data to support the optimum force theory of Smith and Storey (1952).

Hixon et al (1970) went on to state that such factors as differences in age and root area between patients were more important considerations than force magnitude. However, they concluded that within a given patient higher forces generally produced more rapid tooth movement than lighter ones.

A subsequent study by Reitan (Reitan, 1970) may explain the difficulty Hixon et. al.(1969) encountered in determining the ideal force for bodily canine retraction. Reitan noted that when mesially inclined canines with long firmly anchored roots are initially tipped with a light force two small hyalinization zones of short duration are produced. A subsequent force of 150-200 grams is then favorable for bodily movement. He rejects forces of 300 grams as being unnecessarily high (as did Storey and Smith, 1952), as they result in formation of new hyalinized zones.

Sleichter (1971) felt that .5 mm of tooth movement could be achieved with forces up to 1200 grams but recommended 150 to 200 grams as ideal.

Gianelly and Goldman (1971) stated opinions similar to those of Ackerman et. al. (1969) rejecting the notion of a single optimum force. Such factors as:

1. force distribution
2. bone density
3. cellularity of the periodontal ligament and
4. shape of the root

are to a large measure unpredictable and hence uncontrollable. Therefore no precise correlations relating the rate of tooth movement to force magnitude could be made. However they classified forces of 50 to 75 grams as light, and ideal for incisor tipping. Forces in excess of 150 grams were considered heavy, yet they recommended 300 grams be used for cuspid translation.

In 1972 Jarabak and Fizzel correlated the clinical parameters of:

1. pain within or around the teeth

2. mobility of teeth, and
3. jaw reflex

with radiographic data from cephalograms and intra-oral x-rays. No histologic examinations were undertaken. Their data led them to suggest that forces of 2.1 grams per square centimeter of root surface would produce optimal tooth movement.

Boester and Johnson (1974) investigated cuspid retraction clinically in ten adolescent patients using four different forces, namely two, five, eight and eleven ounces.

They recorded the following observations:

1. The two ounce force produced significantly less retraction than did the five, eight or eleven ounce force.
2. The latter three forces produced very nearly equal tooth movement.
3. Anchorage loss as a function of increased force application as reported by Smith and Storey (1952) was not observed.
4. Pain did not appear correlated with increasing force levels as no significant differences were produced by the four force levels employed.

Research has also been done by Ricketts et. al. (1979), Andreason and Zwanziger (1980), Thurow (1982) and Burstone (1985). Again, no general consensus has been reached.

Reitan (1985) in an extensive review of the relevant data, points out that variability between patients in a number of factors may significantly alter the response of the tooth to force application. The parameters he cites are almost identical to those quoted by Gianelly and Goldman (1971) and include:

1. age
2. bone density
3. bone architecture, and
4. cellularity of the periodontal ligament

The above quoted studies recommend a remarkably wide range of forces as being ideal for tooth movement. Though Gianelly and Goldman (1971) and Reitan (1957,1985) suggest recognition of the biologic parameters that differ from patient to patient, it seems unlikely that variability within the periodontium alone could account entirely for the conflicting results. A more likely explanation is that the variability stems from inability to know precisely what forces are being applied to teeth, as discussed in Section 2.1, " Force Systems with Continuous Arches". This has been most recently emphasized by Levin (1985), who showed quantitative data of how force levels may be markedly affected by variations in ligation technique.

Nevertheless, though somewhat inconclusive, the data on threshold levels forms a reference for comparison with the force levels Sullivan (1982) suggests are present on anchor teeth with continuous flexible archwires. The forces Sullivan shows are well above even the highest recommended levels needed for tooth movement. Indeed they are in the range of forces considered by many to be pathogenic to the periodontal ligament (e.g. Reitan,1957).

However the degree to which anchorage loss will occur depends on the ability of the anchor unit to resist the forces placed upon it. Therefore, analysis of the anchorage potential that exits in the region adjacent to malposed teeth should provide insight as to the likelihood of movement when subject to the forces exerted on them.

2.4 ANCHORAGE MODALITIES

" Anchorage has been defined as the supporting base for orthodontic forces that are applied to stimulate tooth movement;the area of application of reciprocal forces that are generated when corrective forces are applied to teeth." (Thurow 1982)

Guilford wrote about anchorage as early as 1905, wherein he recognized that orthodontic force application was not exempt from Newton's third law. Hence, when movement of only one tooth is required, the tooth used as anchorage must be more firmly implanted than the one to be moved, i.e. a molar against an incisor or bicuspid. However, he stated that even a firmly implanted multi-rooted molar could be moved by the reciprocal force produced when moving a tooth of "less fixedness". He therefore suggested four ways by which to secure more stable anchorage:

1. Combine the resistance of several teeth, i.e. join two or more teeth by metal bands soldered together, so that the unit would have to be "dragged" through the alveolar process in their upright positions.
2. Counterbalance the force exerted upon the anchor tooth or teeth in one direction by another force in the opposite direction, thus making the forces reciprocal.

3. Use the teeth in one jaw to move teeth in the opposite jaw, intermaxillary anchorage.
4. Obtain anchorage or resistance at some point outside the mouth.

Dewey (1919) defined anchorage as the resistance used to overcome the applied force that results from force application to the teeth being moved. He stressed that anchorage is one of the most important requirements of a regulating appliance. He proposed a classification scheme whereby anchorage could be described according to a number of parameters.

It was first classified according to the souce of origin:

1. intramaxillary
2. intermaxillary
3. extramaxillary

Secondary classification denotes the number of teeth used for reenforecment:

1. single (also called primary)
2. re-enforced (also called compound)

Third, the manner in which the resistance is obtained is described:

1. Simple - in which a larger or more favorably located tooth is used,
2. Stationary - in which the tooth, if it moves at all will do so bodily through the alveolar process.

3. Reciprocal - in which both malposed and anchor tooth movement is desired.

Accordingly, any situation can be described in terms of its three characteristics, e.g., simple primary intramaxillary anchorage. With simple anchorage resistance is overcome when a force sufficient to tip the tooth occurred. Stationary anchorage is accomplished by constructing the appliance rigidly so as to prevent any tipping movement while reciprocal anchorage could be either simple or stationary.

Strang (1943) and Strang and Thompson (1958) stated that "intraorally there is no true anchor base available for orthodontic use". They felt that the tissues surrounding teeth were not designed for fixation but rather to furnish resistance to displacement and to prevent shock and trauma. As tooth movement unavoidably results in reciprocating forces, anchorage is dependant upon how skillfully the operator limits structural alteration in areas where movement is undesired, while promoting extensive change where tooth shifting is indicated. Therefore they based anchorage preservation on the <u>biologic</u> parameter of controlling periodontal ligament cell reaction to stress and strain. By distributing reactive forces over the anchorage area the intensity of cellular response could be reduced so as to avoid change responsible for tooth movement.

They stated that this is accomplished clinically by controlling the mechanics to establish simple and or stationary anchorage, as defined by Dewey (1919). However, they felt that reciprocal anchorage was a misnomer, and that from the viewpoint of fixation it is in reality reciprocal movement.

Salzmann (1950, 1966) defined anchorage as the resistance from which the force applied to teeth to be moved is to originate. All other things being equal he feels resistance is directly proportional to root area, and may be enhanced by:

1. the manner of interlocking of the cusps
2. the bone in which the teeth are situated
3. muscular pressure
4. growth direction of the teeth.

Salzmann cautioned that teeth not subjected to recent movement are better for anchorage than those that have recently changed position and, hence, are surrounded by highly labile bone. He suggested measures for reenforcing anchorage, including:

1. the use of stabilizing plates,
2. lingual arches positioned at the gingival areas of the tooth crowns,
3. edgewise arches with second order bands,
4. ribbon or flat arches.

Graber (1972) and Thurow (1982) re-enforce the concepts set forth by Strang and Thompson (1958). They maintain that all anchorage must essentially be considered reciprocal. Resistance to movement is accomplished by designing the appliance to distribute the reciprocal forces over significantly different root areas (i.e. a larger root area in the anchor segent) with the objective of eliciting a differential response from different teeth.

The segented arch technique (Burstone 1962, 1966) involves dividing the arch into what Burstone calls the active and reactive (anchor) units. Teeth within reactive buccal segents, which provide anchorage against anterior retraction or cuspid uprighting are connected by .533 x .635 mm (.021 x .025 inch) rectangular archwires. A further increase in root area occurs when the two segents are bound firmly together with an .914 mm (.036 inch) transpalatal arch. Burstone likens the anchorage unit thus produced to a single massive tooth, very resistant to the "continuous" forces produced by his calibrated springs.

In order to prevent molar extrusion with the utility arch. Ricketts et. al. (1979) place a heavy rectangular wire in the slots on the molar and remaining buccal segent teeth. Again, the purpose being to increase the area of the periodontal ligament over which the reciprocal force will be distributed.

2.4.1 Force Levels vs. Anchorage

In a general statement regarding anchorage Salzmann (1966) warned that high forces (though he did not specify level) result in anchorage loss. He did not specify if this occurred universally, whether employing simple or stationary anchorage, or single or multiple teeth.

As noted in Section 2.3.1 Smith and Storey (1952) reported that when forces above 150 to 200 grams are used to retract cuspids, notable anchorage loss occurs, well in excess of the cuspid retraction achieved.

Conversely, Boester and Johnson (1974) reported no such correlation in their investigation of cuspid retraction, while Andreason and Zwanziger (1980) present data somewhat between the two positions.

The lack of correlation between studies may be due to poor regulation of force delivery and or differences in the type of anchorage used.

Better controlled studies are needed before further comment is warranted.

2.4.2 Summary

It appears as though the essence of both intra and inter maxillary anchorage with edgewise appliances employs teeth in the manner of pitting the many against the few, the large against the small.

Stabilization of teeth against movement involves connecting as many teeth as possible with rigid rectangular wires in order to distribute the force so as to keep stimulation of the periodontal ligament to a minimum.

However, the contention that stationary anchorage (Dewey 1919) will be overcome only when the force is such as to stimulate bodily movement has not been clinically confirmed. Even rigidly bound sections of an arch may behave as a single tooth, exhibiting tipping as the response to force application. Indeed this type of tipping is often seen when tear-drop shaped closing loops are used for space closure (Stoner,1960).

Also, regardless of the rigidity of the wire used to construct the Nance holding arch (Nance, 1947), a large distal force directed through the molar tubes (as with cervical headgear) will cause rotation of the molars about a transverse axis through their centers of resistance. This results in the molars tipping back as a unit. Clinically this is manifested by the acrylic button no longer maintaining contact with the palate.

We might therefore anticipate that during alignment with flexible archwires, no more than simple compound anchorage is achieved (Dewey, 1919). An even more likely possibility is that nothing more than reciprocal anchorage occurs (i.e. reciprocal movement, Strang & Thompson, 1958).

Hence serious questions arise concerning the ability to control unwanted tooth movement with low modulus archwires, i.e.

1. how does the lack of any rigid connection between anchor teeth compromise their ability to resist forces?
2. how much will the tooth immediately adjacent to an irregular tooth move before it receives any support from the neighboring tooth?
3. will increasing the number of teeth in the anchor unit compensate for lack of wire rigidity?
4. how do geometry and ligation variables affect anchorage?

2.5 CONCLUSION

It has been speculated for almost fifty years that precise control over tooth movement is compromised when continuous archwires are used to align even moderately irregular teeth. Recent research (Sullivan 1982) has provided three-dimensional data describing the spurious forces and moments exerted in anchorage regions,i.e. those adjacent to malposed teeth, during alignment with flexible archwires. These forces are well above the levels considered necessary to initiate tooth movement. Therefore the degree to which anchorage can be maintained against these forces determines the subsequent control over final tooth positioning.

Among the primary tenants of anchorage control is the principle of stress distribution. Theoretically the coupling of dental units by ligation to a stiff rectangular archwire results in the formation of a single large tooth. The unit is more resistant to forces as the effective periodontal ligament area is increased.

Therefore anchorage potential derived from inter-tooth coupling with the flexible archwires in current use is suspect. Yet the exact nature of the anchorage compromise remains essentially unquantitated, and provides the basis for the present investigation. The technical apparatus necessary to perform such a study has been developed (Paquien, 1978) and used successfully in previous investigations, (Sullivan, 1982, Levin, 1985).

Chapter III

MATERIALS AND METHODS

3.1 INTRODUCTION

As noted in Section 2.2, Sullivan (1982) demonstrated the reciprocal forces and moments occuring on the first tooth next to a buccally malposed tooth. These included:

1. a moment about the occusal-apical axis
2. a buccally directed force
3. a moment about the mesial-distal axis
4. unpredictable forces along the mesial-distal axis

Given the number of effects present, it seemed unrealistic to attempt to study them all simultaneously. Therefore, it was decided to look at anchorage control for rotation about the occlusal-apical axis, as this may be considered to be the influence to which the tooth is initially the most susceptible.

The instrumentation used in this investigation (Fig. 1) was similar to that used in previous studies, (Sullivan, 1982, Levin, 1985). However, as the apparatus was originally designed for linear activations only, modifications were necessary to allow rotational movement in order to meet the requirements of this study. Details of these modifications are discussed later in the chapter.

The three principle components of the apparatus used are:

1. the measuring system
2. the data acquisition system
3. the minicomputer and data storage system

3.2 THE MEASURING SYSTEM

The measuring system contains six transducers which are arranged so as to allow simultaneous assessment of three forces and three moments exerted on a model tooth. The maximum capacity of the transducers is 1300 g of force and 23,000 g-mm of moment. Figure 2 demonstrates the forces and moments as they relate to specific tooth movements of the model tooth on the machine. They are as follows:

1. force in the x direction (Px): force in a buccal-lingual direction.
2. force in the y direction (Py): force in an occlusal-gingival direction.
3. force in the z direction (Pz): force in the mesial-distal direction.
4. moment about the x axis (Mx): rotation about the buccal-lingual axis.
5. moment about the y axis (My): rotation about the occlusal-gingival axis.
6. moment about the z axis (Mz): rotation about the mesial-distal axis.

The measuring system was calibrated, and the accuracy of the measurements was confirmed to be within plus or minus three percent of full scale.

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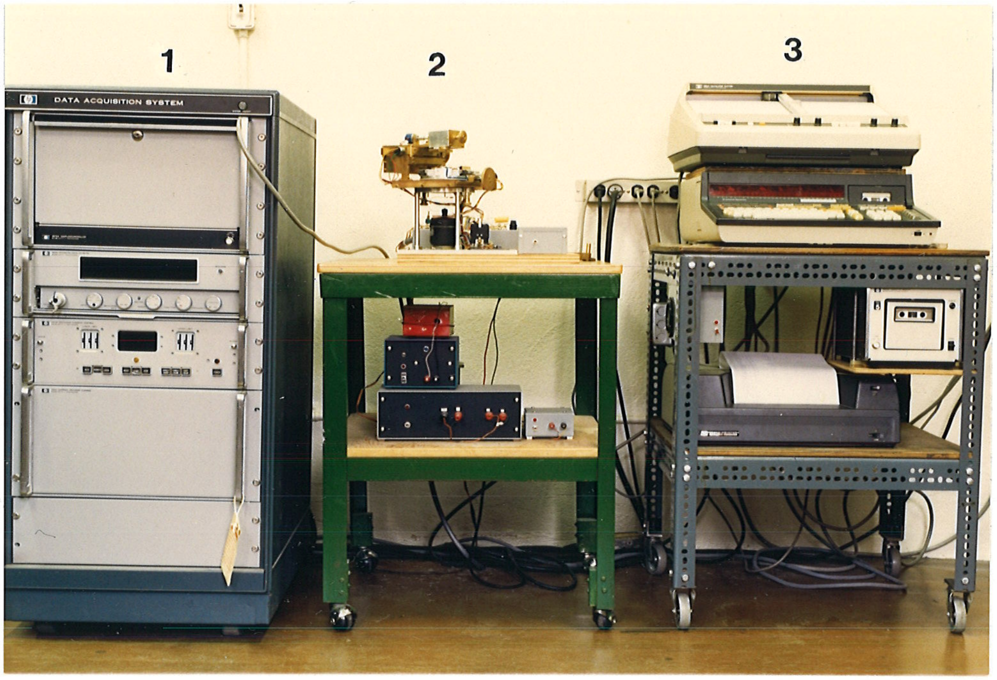

1. Data acquisition system (D.A.S.)
2. Measuring system
3. Minicomputer and data storage system.

Figure 1: General view of instrumentation

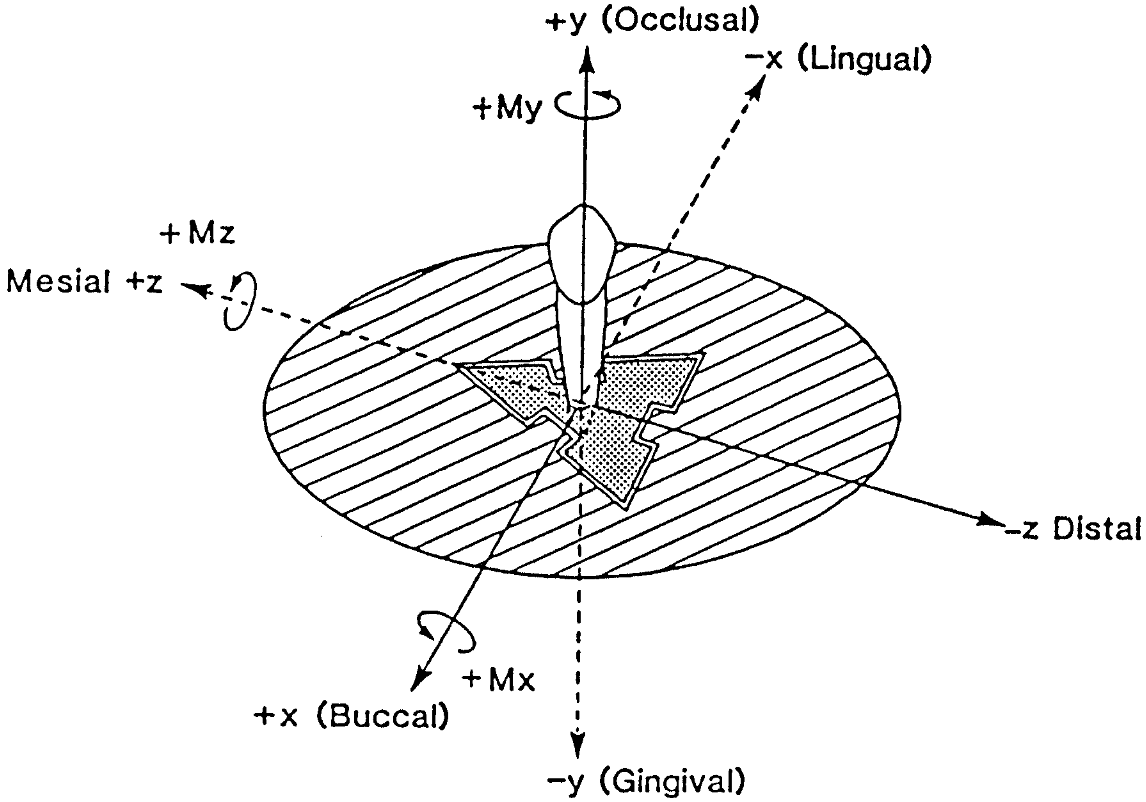

Figure 2: Relationships of the forces and moments to the measured system

3.3 THE DATA ACQUISITION SYSTEM

The data acquisition system (D.A.S.) is a 300 channel Hewlett Packard cross bar scanner. The D.A.S. received input from the measuring system transducers, and relayed it to the minicomputer. Input to the D.A.S. was controlled via the minicomputer, however direct operator control was also possible.

3.4 MINICOMPUTER AND DATA STORAGE

Output from the data acquisition system was relayed to a Hewlett Packard minicomputer model 9830A. Computer programs and data were stored on magnetic tape cassettes with an X-Y plotter and line printer used for data presentation.

3.5 COMPUTER PROGRAMS

The computer programs used in this investigation were modifications of those used by Sullivan, (1982) and Levin, (1985). All programs were written in BASIC.

The data acquisition program dictated procedural order, and allowed keyboard control over experimental variables (i.e. degree and direction of activation, number of steps), and graphic display on the X-Y plotter. Upon completion of an experimental trial, the acquisition program directed data storage onto a separate magnetic tape cassette.

The data analysis program was used to convert data stored on magnetic tape to an easily analyzable form on the X-Y plotter. In this way a variety of relationships between force, moment, and activation could be designated. Uniformity of graphic presentation was achieved by designating the x-axis proportional to activation, and the y-axis proportional to force and/or moment.

3.6 ACTIVATION SYSTEM DESIGN

The system used in this study is based on the apparatus employed by Levin (1985). Ormco cuspid/bicuspid brackets with no tip or torque in the slot relative to the base were used. The "teeth" employed in this study were brass block models (Fig. 3). The dimensions of the brass blocks were uniform and constant in all 3 dimensions. Typical dental terminology is used to describe the size, orientation, and movement of these teeth.

The middle and left end teeth had tapped screw holes on their superior surfaces to allow attachment to the activation system. The right end tooth was secured to the measuring system through a countersunk hole in that tooth. The labial surfaces of the blocks were curved to match the radius of curvature of the bonding bases of the Ormco brackets. This facilitated accurate adaptation of the bracket to the model teeth.

The method for mounting the brackets to the model teeth was based on the technique employed by Levin (1985).

An interbracket distance of 6.7 mm was set and initially maintained by stainless steel spacer blocks between the three teeth. This corresponded to a 10 mm distance between the centers of the brackets

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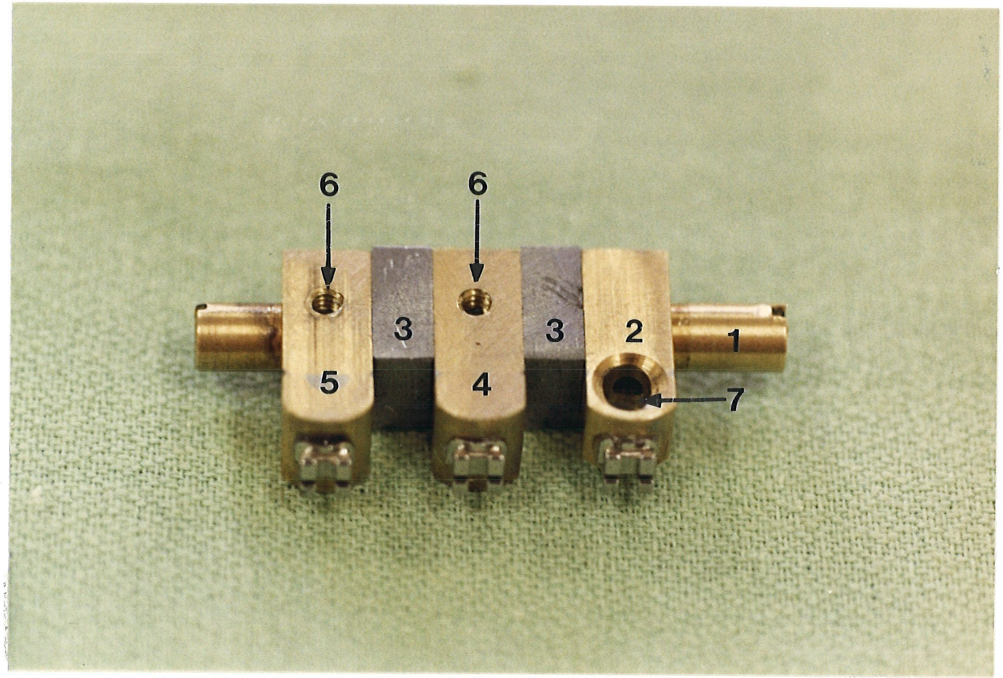

1. threaded bolt
2. brass right tooth (measured tooth)
3. steel spacer block
4. brass middle tooth
5. brass left end tooth
6. tapped screw hole
7. countersunk hole

Figure 3: Three tooth assembly

(Fig. 4). A previous study, (Sullivan, 1982) demonstrated that using interbracket distances of between 2 and 4 mm. caused plastic deformation of the archwire to readily occur. It was felt that the larger interbracket distance would help avoid the excessive force levels causing the plastic deformation , and could represent a clinical situation occurring in the molar segment.

A threaded bolt passed through the teeth and spacer assemblage and was tightened with a washer and nut. An aluminum jig with a rectangular slot was used to keep the teeth and spacers aligned and flush while the alignment bolt and nut were tightened. The three tooth assembly was stabilized within the slot by retaining pins. The stability was further enhanced by having the jig attached to a heavy steel plate (Fig. 5). This arrangement allowed convenient wire insertion and ligation. The entire tooth/archwire assembly could be released from the jig by removing the retaining pins. Before being mounted on the measuring system, the three teeth were further connected by a brass holding jig, held by screws to the lingual surfaces of the teeth. When the jig was secured, the threaded bolt and spacers were removed from the assembly, leaving the teeth attached now only by means of the jig and the archwire (Fig. 6).

The entire assembly including ligated archwire was then attached to the inferior surface of a brass plate by means of threaded screws to the middle and left end tooth only. The brass plate holding the teeth also supported a vertical brass sleeve at each end of its superior surface (Fig. 6). The three teeth, jig, and plate (including sleeves) were then attached to the measuring system by a screw through the right end tooth only.

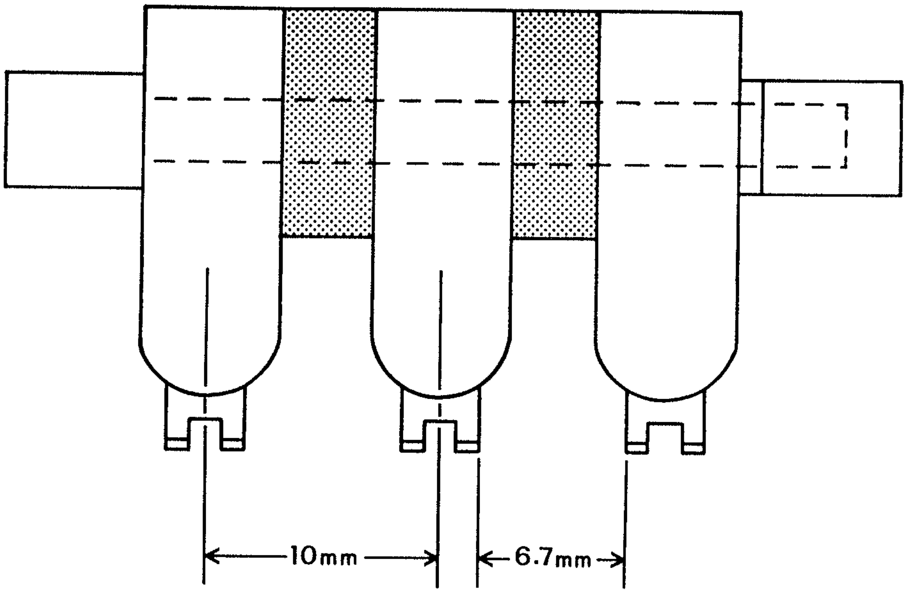

Figure 4: Three tooth assembly - interbracket dimensions

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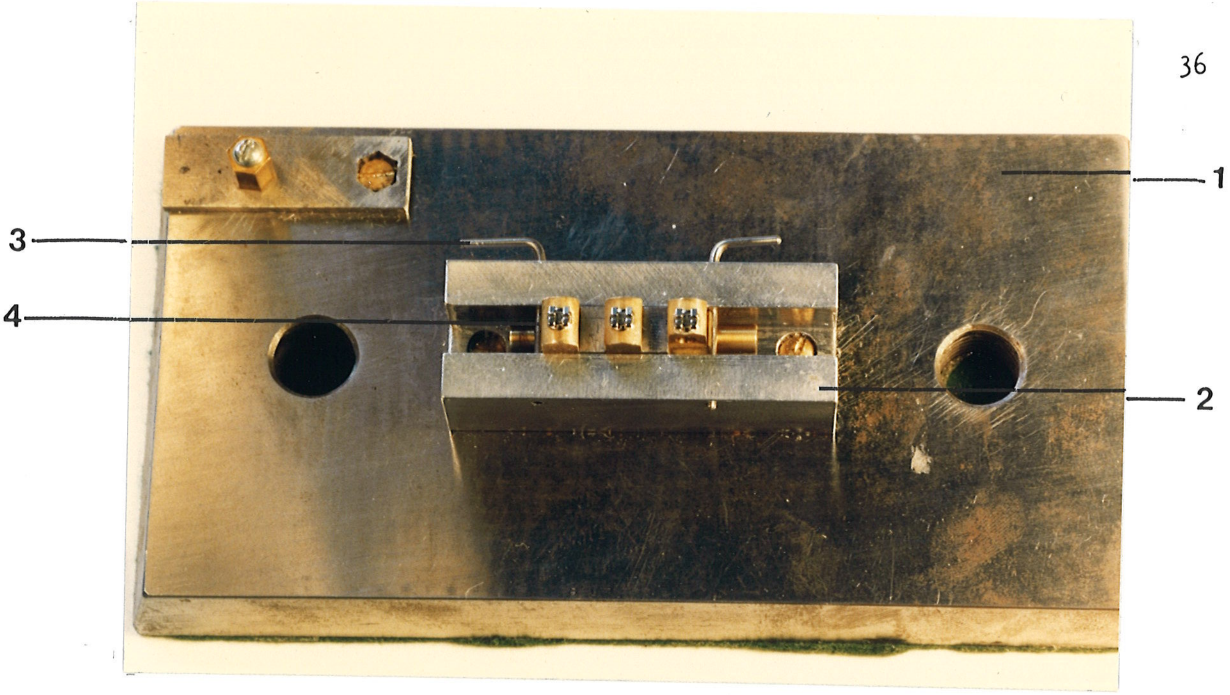
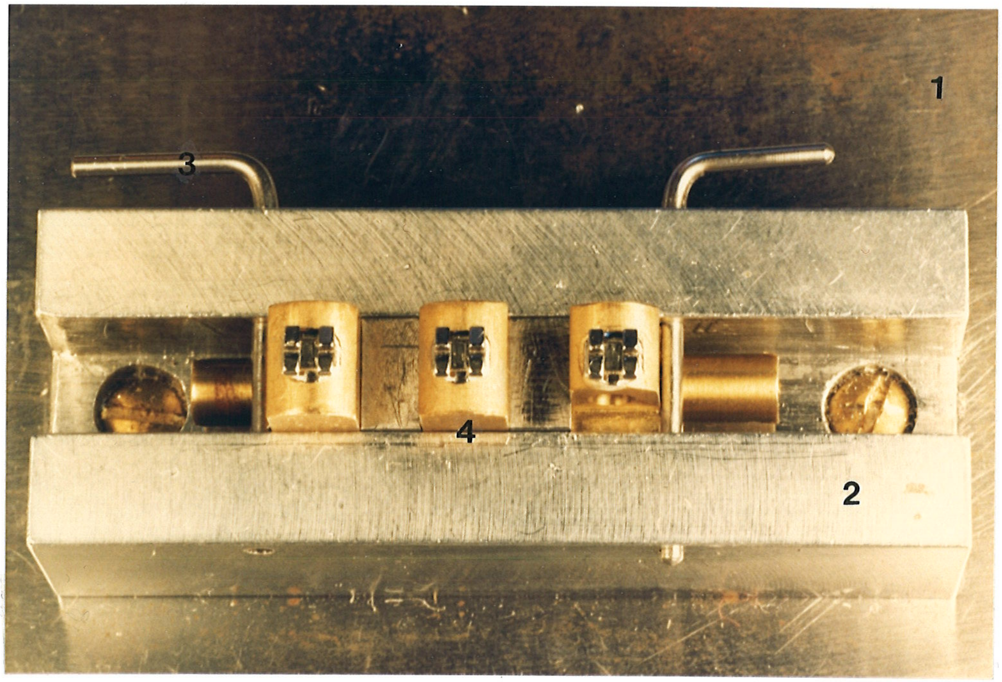
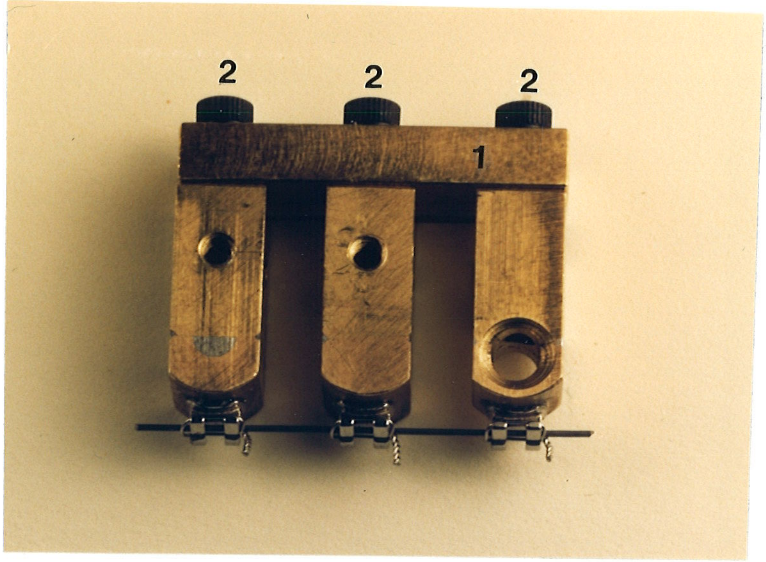




Close-up

1. stabilizing steel plate
2. aluminum alloy jig
3. retaining pins
4. three-tooth assembly

Figure 5: Aluminum alloy holding jig and stabilizing plate



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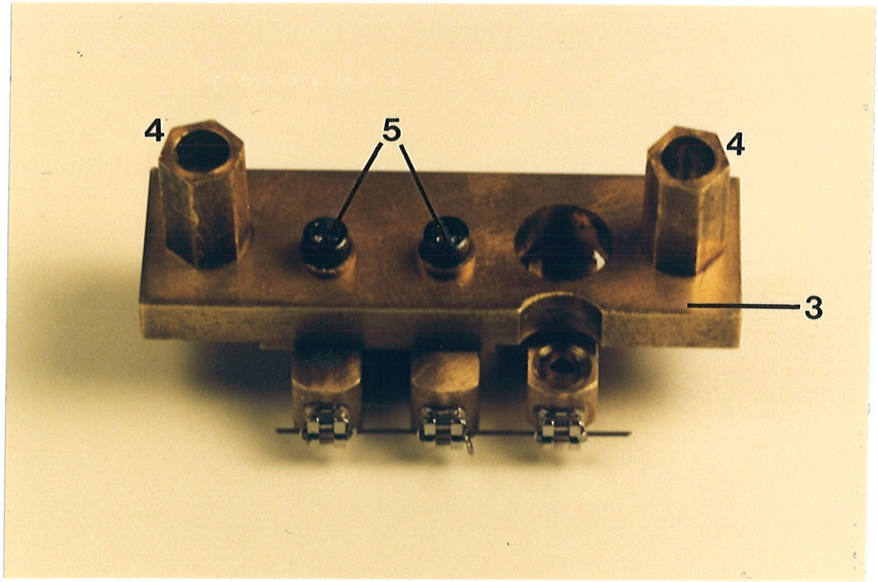


BOTTOM

1. brass jig
2. screws attaching brass jig to three-tooth assembly
3. lower brass plate
4. brass sleeves
5. screws attaching middle & left end tooth to brass plate

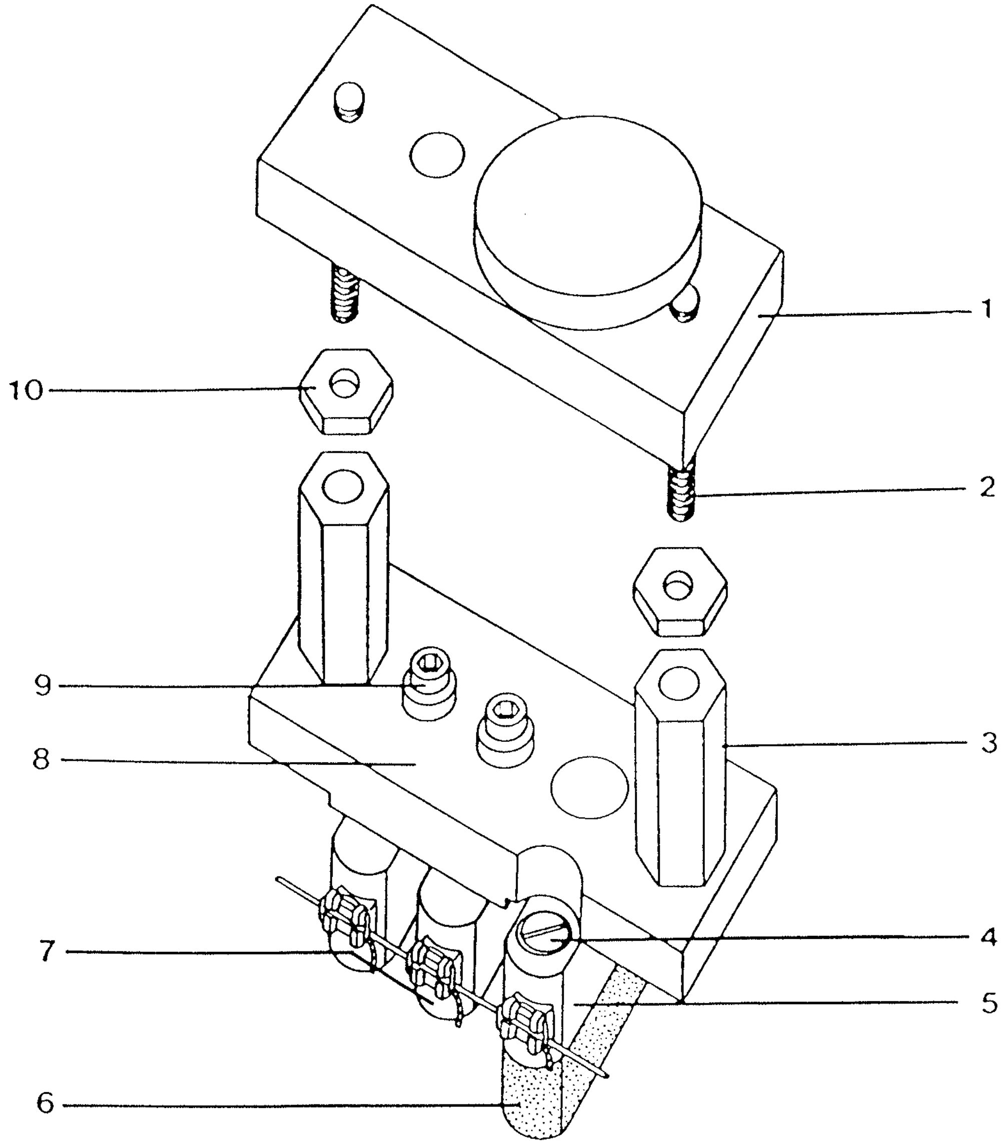
Figure 6: Top- Three tooth assembly with lingual holding jig, Bottom - Three tooth assembly mounted to lower brass plate

A second brass plate permanently attached to the activation system had threaded pins projecting from its inferior surface. The apparatus was constructed to allow the threaded pins to be lowered into the brass sleeves without contacting them at any point. This was preceeded by inserting composite resin (Kerr Resin Bonded Bridge Cement) into the sleeves, after which the pins were inserted and the resin allowed to set.

Upon setting of the resin, the lower plate/tooth assembly was firmly attached to the upper plate and hence the activation arm of the instrument.

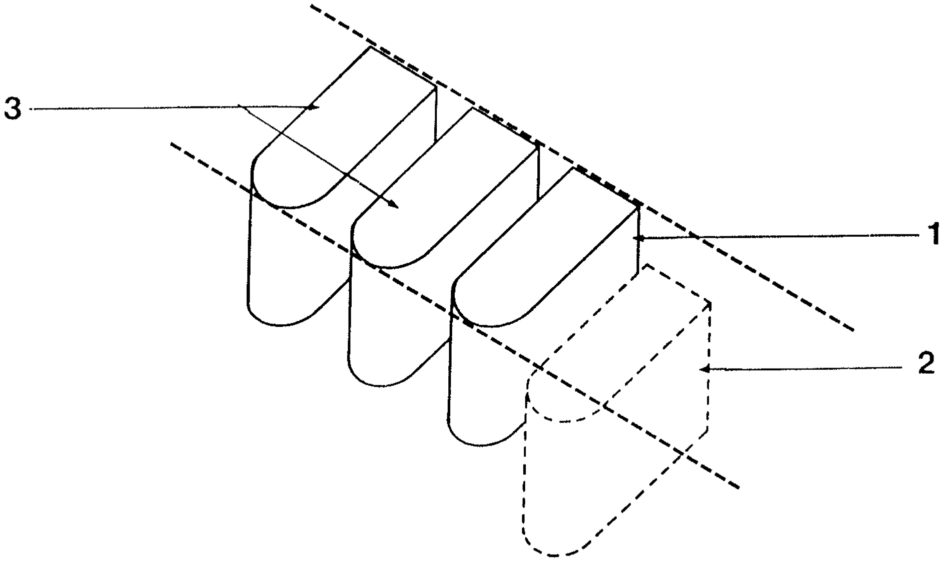
Removal of the brass holding jig resulted in only the right end tooth remaining attached to the measuring system, and hence stationary. The two remaining teeth via the brass plates, sleeves, and resin travelled with the activation arm. The three teeth remained connected now only by the ligated archwire. Hence the forces and moments generated during activation acted only on the right end tooth and measuring system (Fig. 7).

As noted above an activation system capable of rotational movement was necessary for the present study. The measured tooth (right end tooth) represents the tooth immediately next to a theoretically malaligned tooth (Fig. 8). Since the measured tooth is attached to the immobile measuring system, it was felt that its movement could be accurately simulated by rotation of the remaining two teeth in accordance with whether a malaligned tooth was buccally or lingually displaced.



1. upper brass plate
2. threaded pin (inserts into resin)
3. brass sleeves
4. screw securing right end tooth to measuring system
5. right end tooth (measured tooth)
6. measuring system component
7. adjacent teeth
8. lower brass plate
9. screw securing adjacent teeth to lower brass plate
10. nut securing threaded pins to upper brass plate

Figure 7: Procedure for attaching upper and lower brass plates



1. measured tooth

2. malaligned tooth

3. adjacent teeth

Figure 8: Relationship of measured tooth to malaligned tooth

For example, for a tooth in buccal malalignment, the first tooth next to it (the measured tooth in our study) was noted to experience a clockwise rotational tendency (Sullivan 1982). This could be simulated by rotating the activation system (containing the other two teeth) in a counterclockwise direction. The axis of rotation was through the center of resistance of the measured tooth.

Modifications of the original apparatus were performed by McLachlan which allowed rotational precision to within one degree. Figures 9 and 10 represent general and detailed views of the apparatus respectively. Figure 11 presents views of the apparatus in both unactivated and activated states.

Maximum activations of 10 or 15 degrees were employed. Five activation points, representing, either 2 or 3 degrees of movement were selected. Activation distances were selected by the operator, (the author) monitored by the linear voltage displacement transducers (L.V.D.T.) and controlled by the minicomputer.

The activation system contains additional features to help simulate the clinical situation. The measuring device permits a .2 mm deflection of the measured tooth at the bracket when fully loaded, hence, approximating the in vivo case. A vibrating system, which applies consistent vibration simulates the effects of mastication and occlusal interdigitation on the orthodontic appliance.

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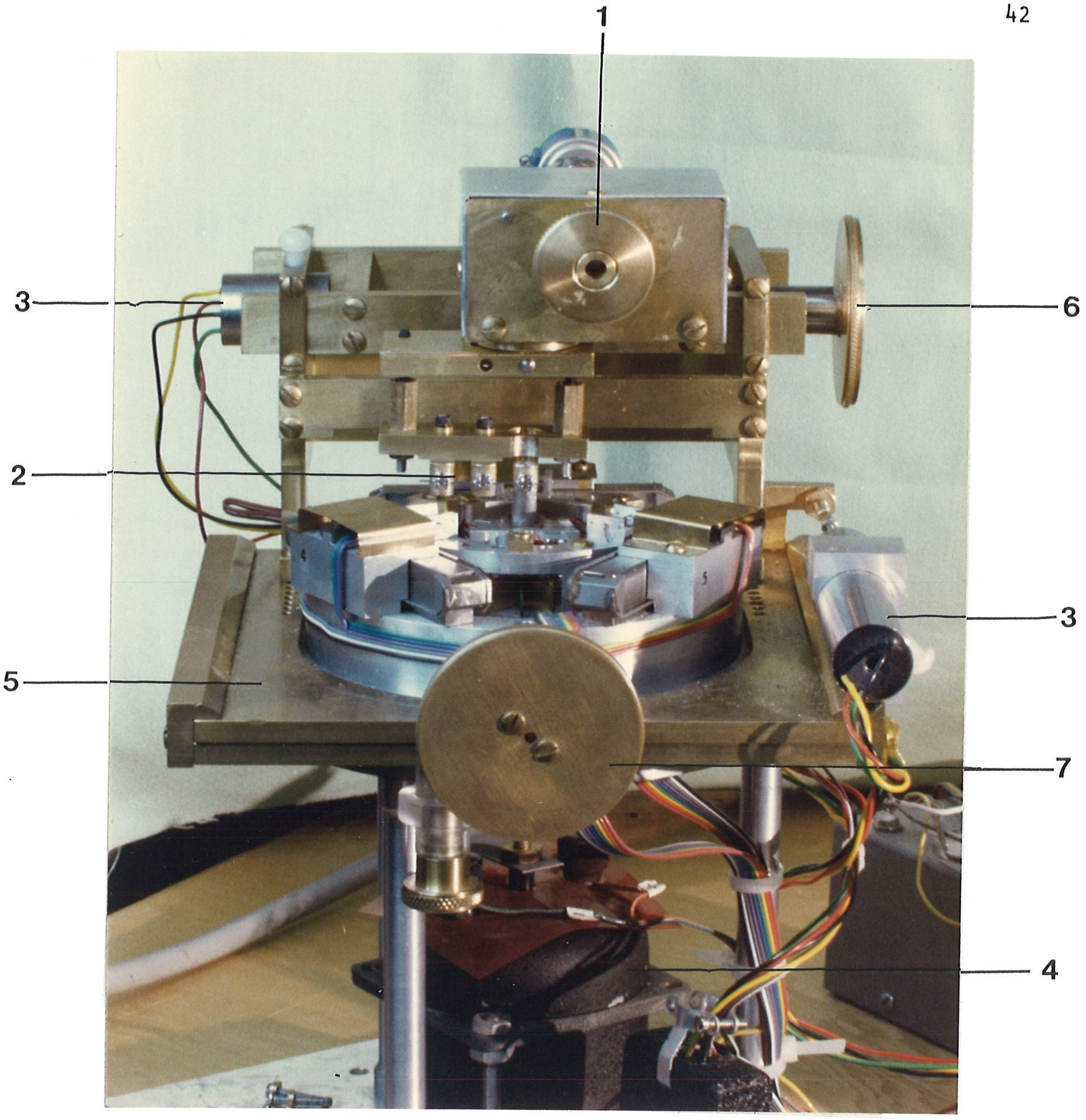
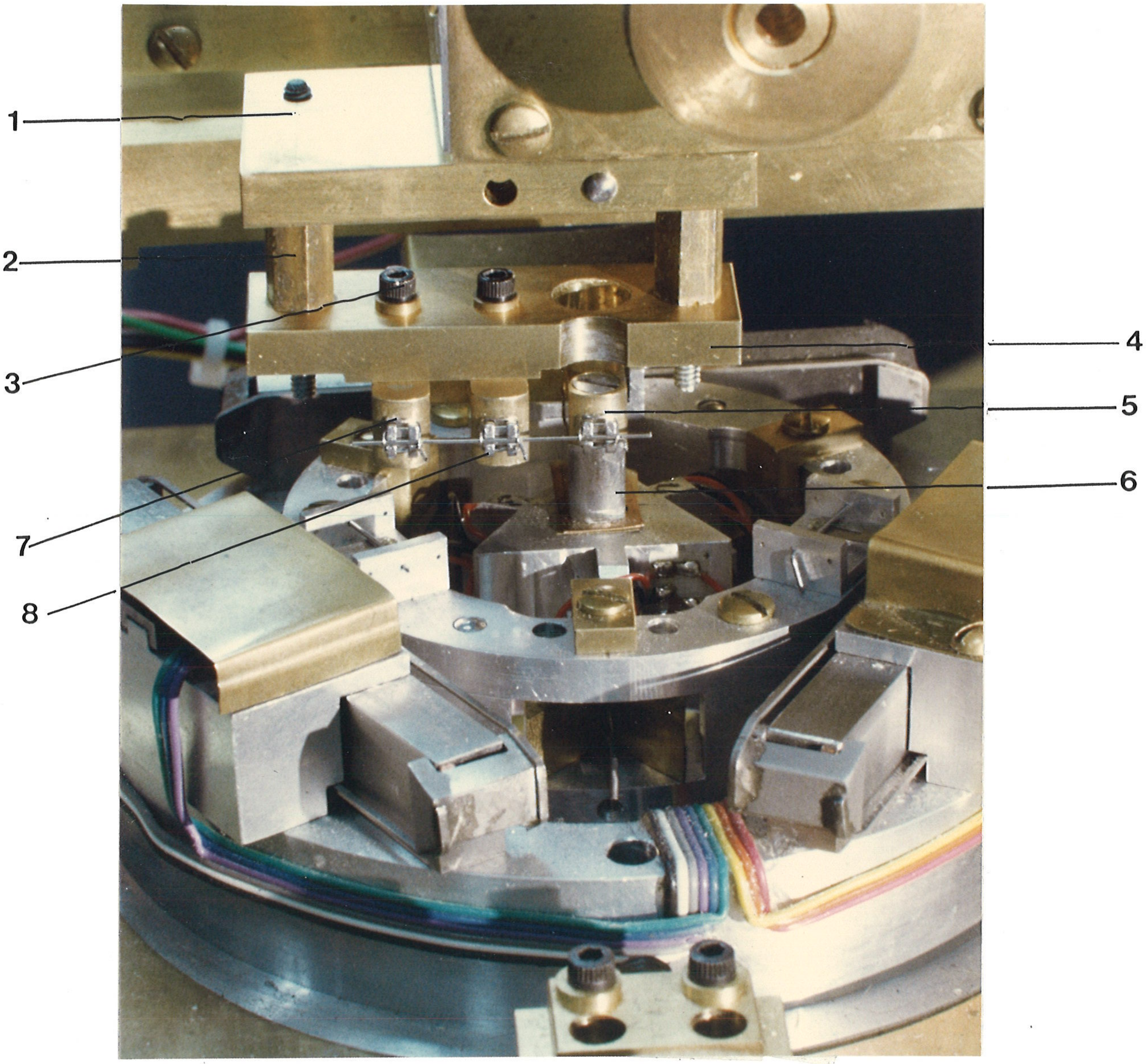


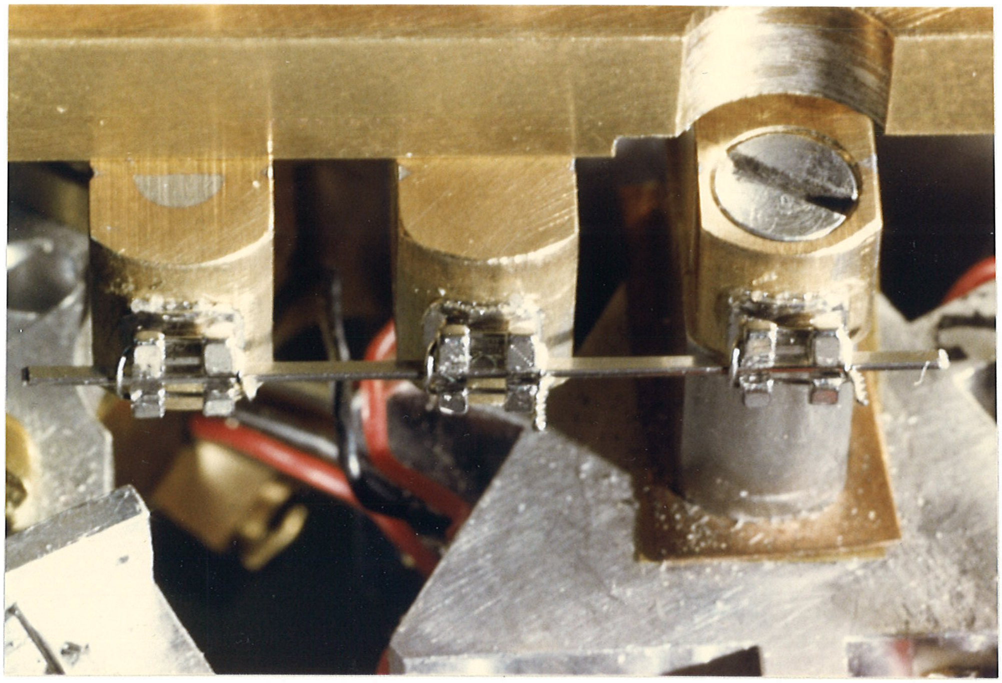
1. rotational activation screw (± My)
2. three tooth segment
3. L.V.D.T. (linear voltage displacement transducers)
4. vibration apparatus
5. horizontal activation plate
6. transverse activation screw (± z)
7. horizontal activation screw (± x)

Figure 9: General view of the instrument



1. upper brass plate
2. brass sleeves (containing resin)
3. screws attaching adjacent teeth to lower brass plate
4. lower brass plate
5. right end tooth
6. measuring system
7. left end tooth
8. middle tooth

Figure 10: Detailed view of instrument



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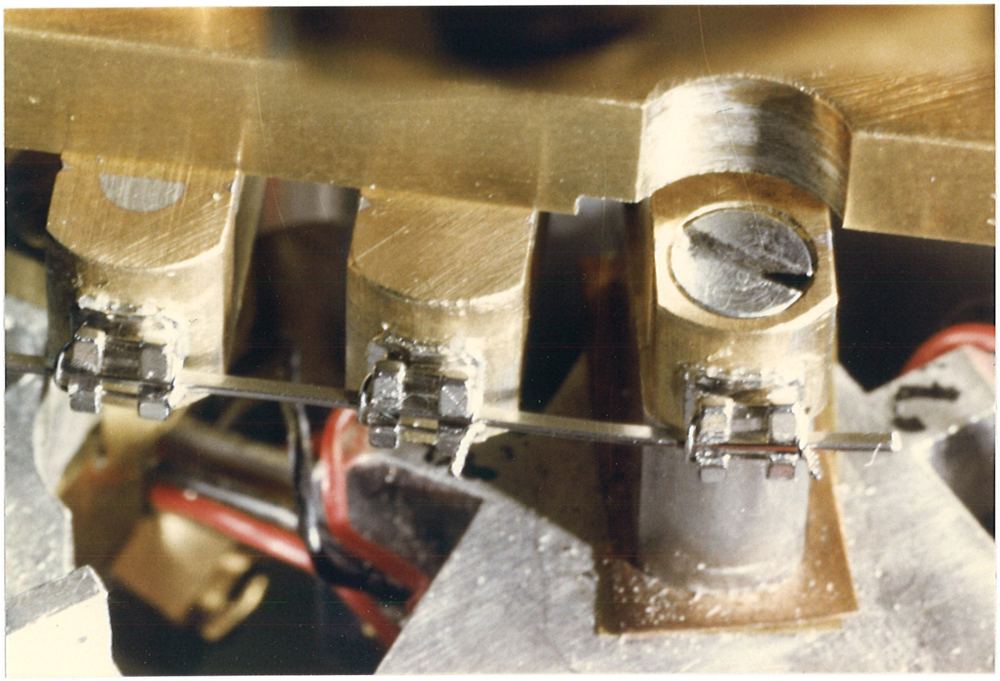

Bottom

Figure 11: Top - unactivated view, Bottom - activated view

Vibration is applied before initial readings and at every step of the activation process.

3.7 EXPERIMENTAL PROCEDURE

The format of the experimental trials involved ligating the archwire to the brackets at the workbench, followed by subsequent mounting to the measuring machine. Disassembly and subsequent remounting following any particular trial run proved time consuming, due to the time required to mix and allow the resin to set. This time lag was avoided by mounting the teeth as described but without the archwire ligated in place. It was felt this was permissible, as the ligation technique was not under investigation. By monitoring the force levels as the archwire was ligated to the teeth it was ascertained that the machine was not overloaded by the ligation process. Hence once the resin had set, a number of trials could be carried out, conserving time and material.

3.8 THE MODEL TOOTH

The measured tooth in this study was actually composed of two separate components (Fig. 12). The superior component was the right end tooth of the three tooth assembly, and as mentioned was made of brass. The inferior component was made of steel and was rigidly attached to the measuring system. The two parts were connected by a screw. With both parts in place the dimensions of the model tooth are representative of a typical dental unit (Fig. 13).

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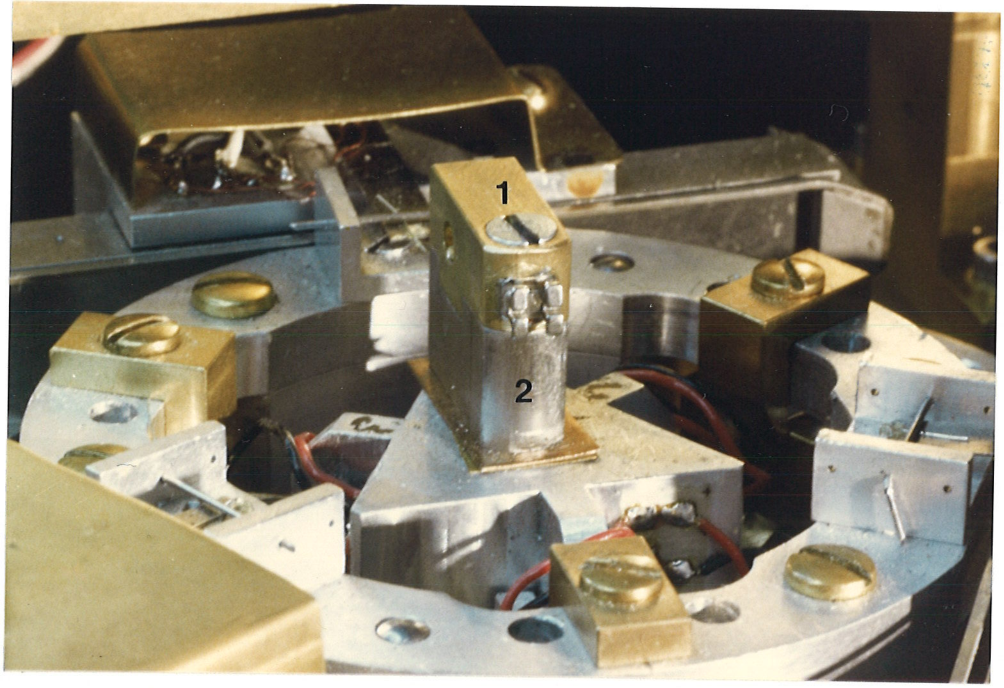

1. right end tooth

2. measuring system

Figure 12: Model tooth

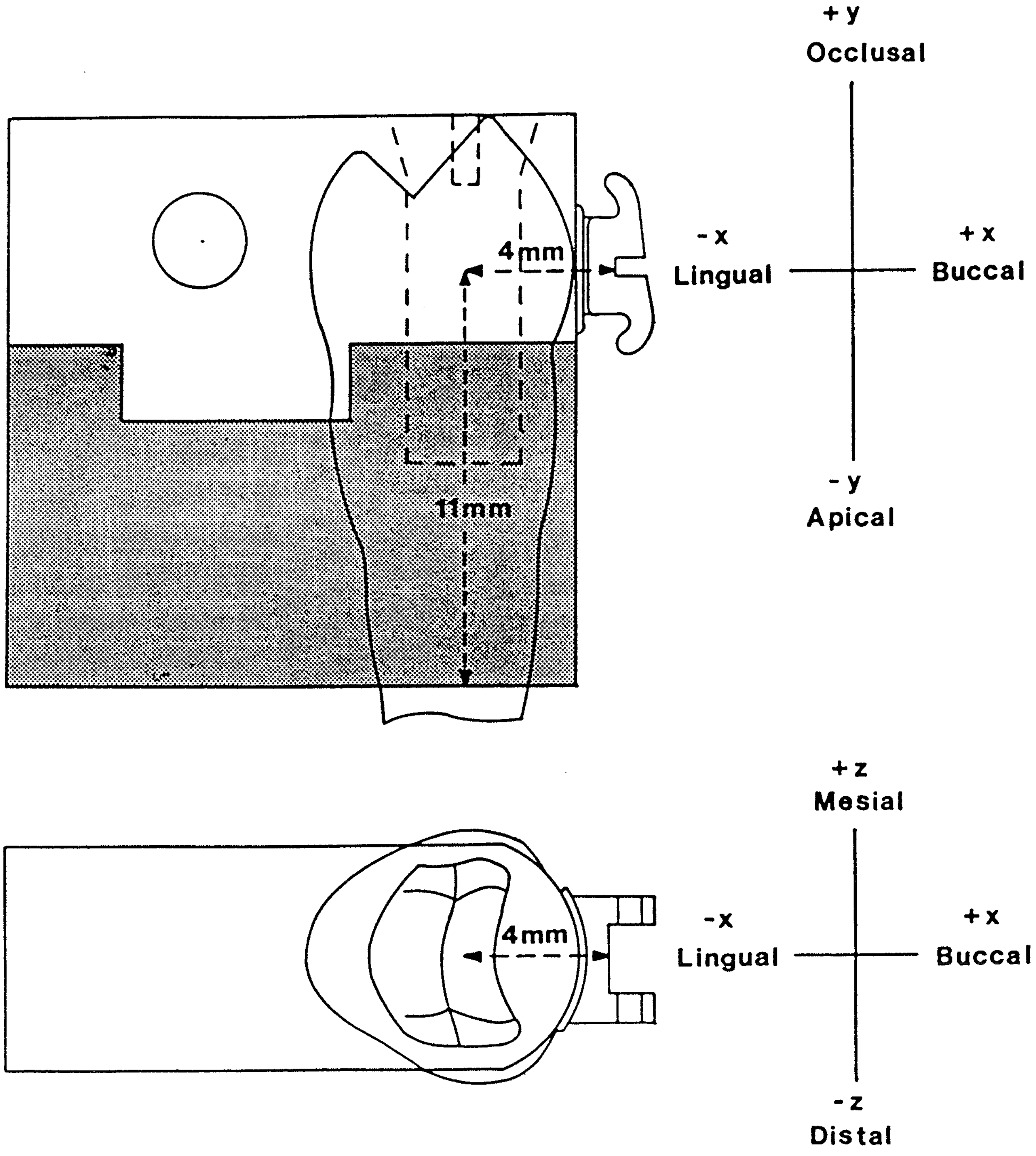

Figure 13: Relationship of model tooth to anatomical tooth

3.9 WIRES TESTED

A number of "light" wires commonly used for initial alignment were employed in the study. These included .381 mm (.015 inch) twistflex, .406 mm (.016 inch) Nitinol and .406 mm (.016 inch) T.M.A. All wires were 30 mm. in length.

As the apparatus was readily able to accommodate rectangular wire, it was felt that investigating the anchorage capacity of these "heavy" wires would provide for interesting comparisons with the lighter wires. This proved to be the case and a number of unexpected and surprising results were observed. Details are discussed in the next section.

3.10 LIGATION TECHNIQUE

The investigation employed predominantly .254mm (.010 inch) stainless steel ligatures. However the results indicated that trials employing .305 mm (.012 inch) ligatures might provide further insight and clarification of the observed effects. Hence, a limited number of experimental trials were tied with this size ligature. Ligatures were tied according to the method recommended by Thurow(1982). The technique involves establishing the ligature tension by hand with the first half turn of the wire. The tying was completed with a Mathieu needle holder,which was used to twist the ligature wire to maintain the established tension. The ligation was performed so as to contain the archwire completely within the bracket slots. As such, every attempt was made to keep the ligature tension identical for each experimental trial.

The center tooth was ligated first, followed by the left, then the right end tooth. The pigtail tie that remained after cutting the ligature was on the right side of the bracket for all three teeth (Fig. 6)

3.11 SPECIAL LIGATION

A number of experimental trials employed a figure-of-eight ligation technique. This involved using only one ligature to secure the archwire in the brackets of all three teeth. After threading the ligature around the three brackets, the tension of the tie was established with the initial half twist of the wire around the right end tooth, in the manner identical to that used for individual ties. The figure-of-eight was always initiated on the left end tooth and tied around the right end tooth with the pigtail tie oriented to the right.

3.12 DATA ANALYSIS

The data analysis program stored the data for subsequent display, either graphically on the X-Y plotter or on the line printer.

A number of relationships were plotted and investigated. The horizontal axis always represented the degree and direction of activation (rotation) and was designated Ay. The vertical axis represented either force or moment magnitude and direction:

1. Px/Ay: the force to activation ratio (buccal-lingual).

2. Py/Ay: the force to activation ratio (occlusal-apical).
3. Pz/Ay: the force to activation ratio (mesial-distal).
4. Mx/Ay: the moment to activation ratio (about the buccal-lingual axis).

5. My/Ay: the moment to activation ratio (about the occlusal-apical axis).

6. Mz/Ay: the moment to activation ratio (about the mesial-distal axis).

By examining these relationships, the three-dimensional characteristics likely to occur at various activations could be studied.

Chapter IV

RESULTS

The objective of this study was to examine the forces and moments which support the first tooth in an anchor segment when it is subjected to rotational displacement. The investigation employed a theoretical three tooth anchor unit in which the measured tooth represented the dental unit immediately next to a buccally or lingually malposed tooth. To facilitate ease of discussion, the measured tooth will be referred to as the FIRST IN LINE tooth. The measuring system was designed to monitor the forces and moments on the first in line tooth as the tooth was subjected to angular displacement. The displacements may be considered typical of what may be anticipated to occur clinically. Angular displacements were accomplished by rotating the two teeth adjacent to the FIRST IN LINE tooth. These teeth will henceforth be referred to as the ADJACENT teeth.

Analysis of the results is based on determining the rigidity of the connection between the three model teeth. A rigid connection would require a high force per degree of activation, whereas a flexible connection would be reflected by a low force per degree of activation. Therefore, the magnitude of the forces and moments generated on the FIRST IN LINE tooth per degree of activation of that tooth was examined to determine the degree of support it received from the two ADJACENT teeth.

4.1 DATA PRESENTATION

Data from the experimental trials will be presented graphically in this chapter. For the most part the discussion will refer to graphs of individual experimental trials (Figures 14 to 33). However, graphs demonstrating the average values of four experimental trials were also constructed (Appendix Fig. A11 - A14). For these graphs the conditions being tested (i.e. archwire dimension, ligation, degree of activation) are kept constant, and hence they allow evaluation of the consistency of the results under identical conditions. The force and moment readings per degree of activation are extended vertically to indicate plus and minus one standard deviation.

The graphs presented in this thesis are constructed such that the horizontal axis represents the angular activation (Ay) marked off in 2 or 3 degree intervals. The vertical axis represents both force and moment such that each increment represents a force of 200 gm and/or a moment of 4000 g-mm. The plots presented here are photocopies of the originals obtained from the computer.

For all plots the initial values of zero represent the unactivated condition in which all three teeth are aligned. Activation brings the two ADJACENT teeth into angular displacement with the FIRST IN LINE tooth, and is represented by the solid line on the graph. Subsequent deactivation brings the teeth back into alignment, which is represented on the graph by the dotted line. Plots obtained for counterclockwise rotation of the ADJACENT teeth appear on the right hand side of the graph, and will be referred to as positive activation. Plots obtained for a clockwise rotation of the ADJACENT teeth appear on the left, and will be referred to as negative activation.

4.2 WIRES TESTED

To illustrate the primary features of the results for low modulus archwires, the data obtained for .406 mm (.016 inch) Nitinol are included in this section. Data representative of 'heavy' wires will be based on the results for .406 x .559 mm (.016 x .022 inch) stainless steel wires. A complete set of plotted results is located in the Appendix for direct comparisons of all data obtained.

The essential feature of an anchorage unit is to resist movement when forces are placed on it. A previous study (Sullivan, 1982) showed that the FIRST IN LINE tooth next to a malaligned tooth is subject to significant reciprocal forces. For this tooth to resist these forces, support (anchorage) must be provided by its connection via the archwire to ADJACENT teeth. Therefore in the present study, resistance to movement (anchorage capacity) is evaluated by analyzing the force magnitude required to rotate the FIRST IN LINE tooth which is coupled to the two ADJACENT teeth by means of the archwire. Comparison of these forces with those thought to act on the first in line tooth resulting from its connection to a malaligned tooth via the same archwire provides the basis for anchorage evaluation.

Therefore plots of the moment about the y-axis relative to the angular activations (My/Ay) will be presented for analysis (Fig. 14 - 33). High values for these plots (based on Sullivan's data, 1982) would be indicative of good anchorage. Low values on the other hand, would indicate a poor resistance to movement.

The presence of additional forces and moments such as Px, Pz, Mx and Mz also merit observation. In order to avoid the confusion that might arise from placing all plots for a trial on one graph, data for one experimental condition (i.e. .406 mm Nitinol, positive activation) will be displayed in sequential graphs, i.e. Fig. 14 & 15. Plots for My/Ay, Px/Ay and Mz/Ay will appear on the first graph, with Pz/Ay and Mx/Ay appearing on the second. For a number of graphs, the plot values are so low that overlapping becomes a problem in distinguishing individual plots. To prevent this, these graphs will be presented such that individual values will be plotted to a common vertical axis, but relative to separate horizontal axes. A second format will also be used in which the initial values are made equal to zero and the magnitude of their relative values multiplied by a factor of five. This allows a more accurate examination of these small value plots.

4.3 DEACTIVATION

Though deactivation as performed on the machine is not a clinical occurance, the return plots are extremely important for explaining many of the observed phenomenon, particularly the large hysteretic effect observed with heavier archwires (Figure 18). It was speculated that the hysteresis was due to deformation of the ligature constraining the wire in the bracket. If this were the case, then repeated, alternating, positive and negative activations should show progressively decreasing hysteresis. In order to test this speculation, one set-up with .406 x .559 mm (.016 x .022 inch) stainless steel wire with .254 mm (.010 inch) ligatures was mounted to the machine. As illustrated by the plots in Figure 20, activation and return in one direction was followed by activation and return in the opposite direction on the same set-up with no change of archwire or ligature. Repeating this cycle an additional two times (Figures 21 and 22) provides evidence to support the above stated speculation and indicates that ligation may play a previously unthought of role when attempting to establish rigid anchorage units. Based on these results, the effect of increasing the size of the ligature was investigated. The results obtained using .305 mm (.012 inch) stainless steel ligatures are found in figure 23.

4.4 SPECIAL LIGATION

The role of ligation was further investigated by examining the effect of a figure-of-eight ligature tie. Figure 28 illustrates the plot obtained with a .406 x .559 mm (.016 x .022 inch) stainless steel wire when the ADJACENT teeth are rotated counterclockwise. When compared with the plot for the opposite activation, (Figure 32) a very large disparity becomes evident. This led to speculation that position of the malaligned tooth relative to the FIRST IN LINE tooth (as this determines the direction of the reactive moment) becomes the critical factor in determining whether substantial or virtually nonexistant anchorage is achieved, this being the case, regardless of the size of archwire connecting the teeth. This hypothesis was tested by repeating trials with a figure-of-eight tie using .406 mm. (.016 inch) Nitinol. These plots are illustrated in figures 26 and 30.

4.5 SUMMARY

In orthodontics, it is common during initial alignment procedures to connect a malaligned tooth to the rest of the arch via low modulus continuous archwires. The resultant forces on the malaligned tooth as well as the reactive forces on the next in line tooth have been investigated (Sullivan, 1982) and shown to be substantial, even with these apparently flexible archwires.

The results presented in this thesis represent the forces and moments available to the FIRST IN LINE tooth to resist these reactive forces. Such resistance (or anchorage) can be provided only by means of the arch wire connecting the FIRST IN LINE tooth to its ADJACENT teeth. Hence, the anchorage capacity of the wires under investigation may be evaluated.

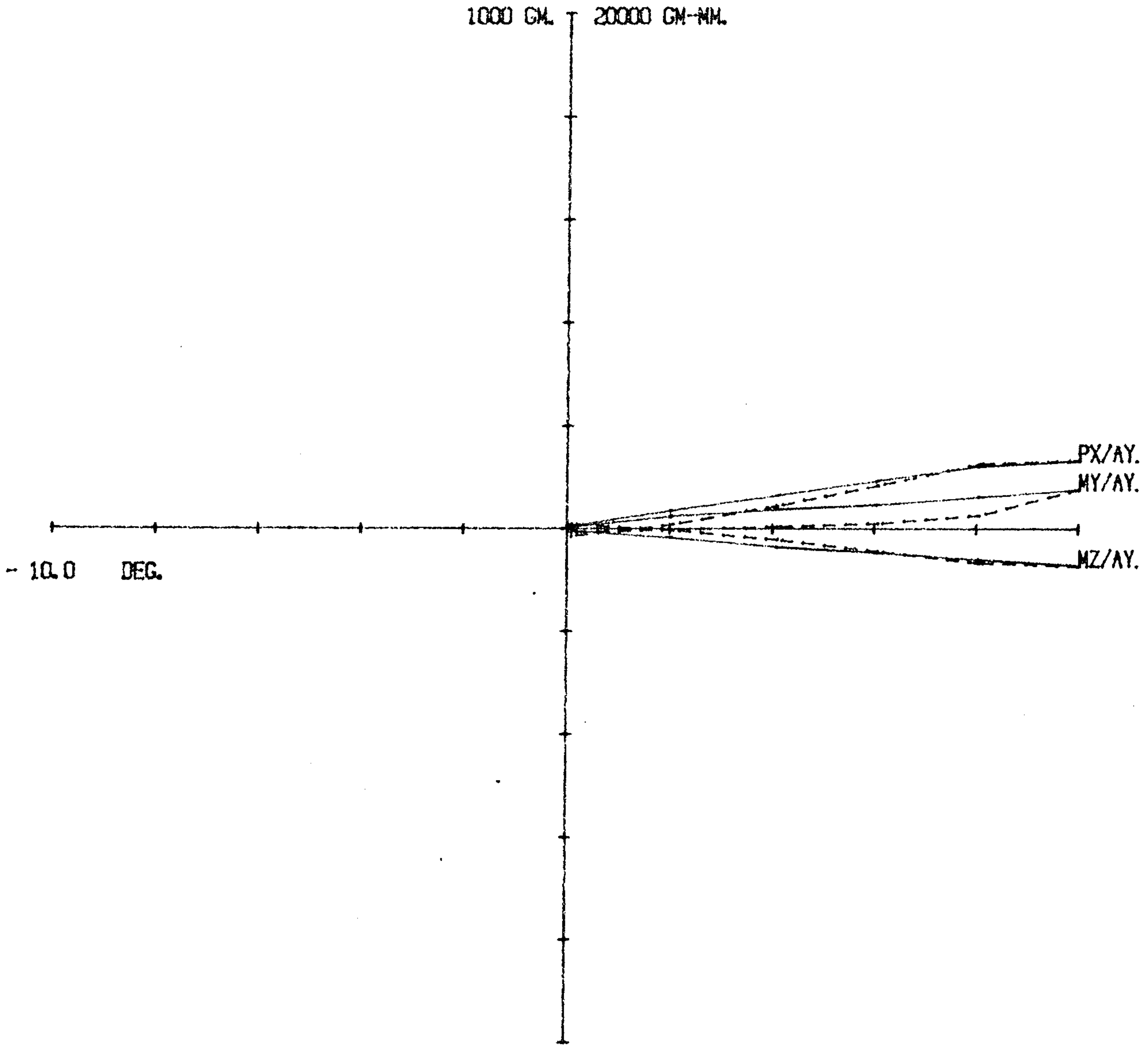

Figure 14: .406 mm (.016 inch) Nitinol - positive activation

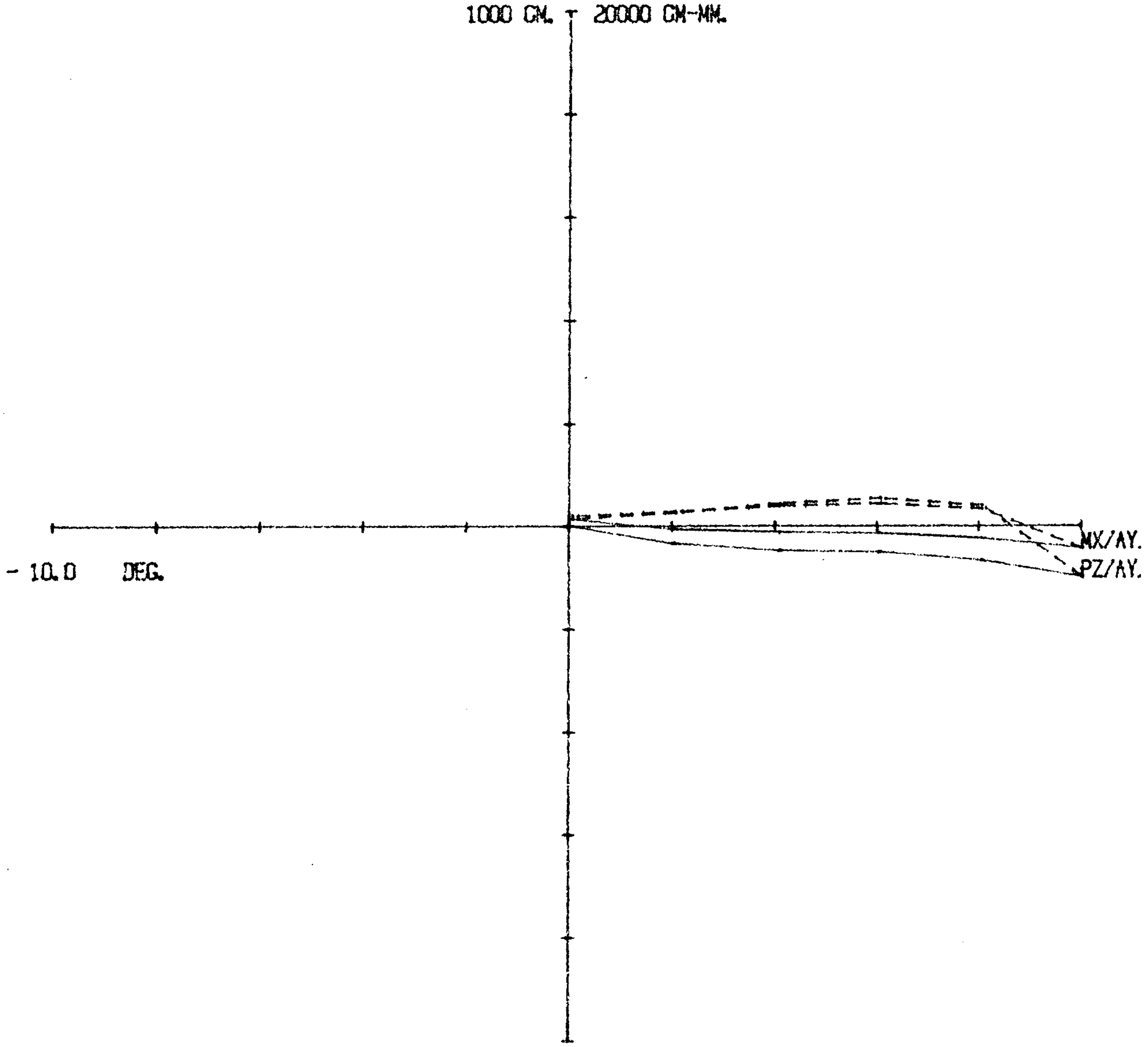

Figure 15: .406 mm (.016 inch) Nitinol - positive activation

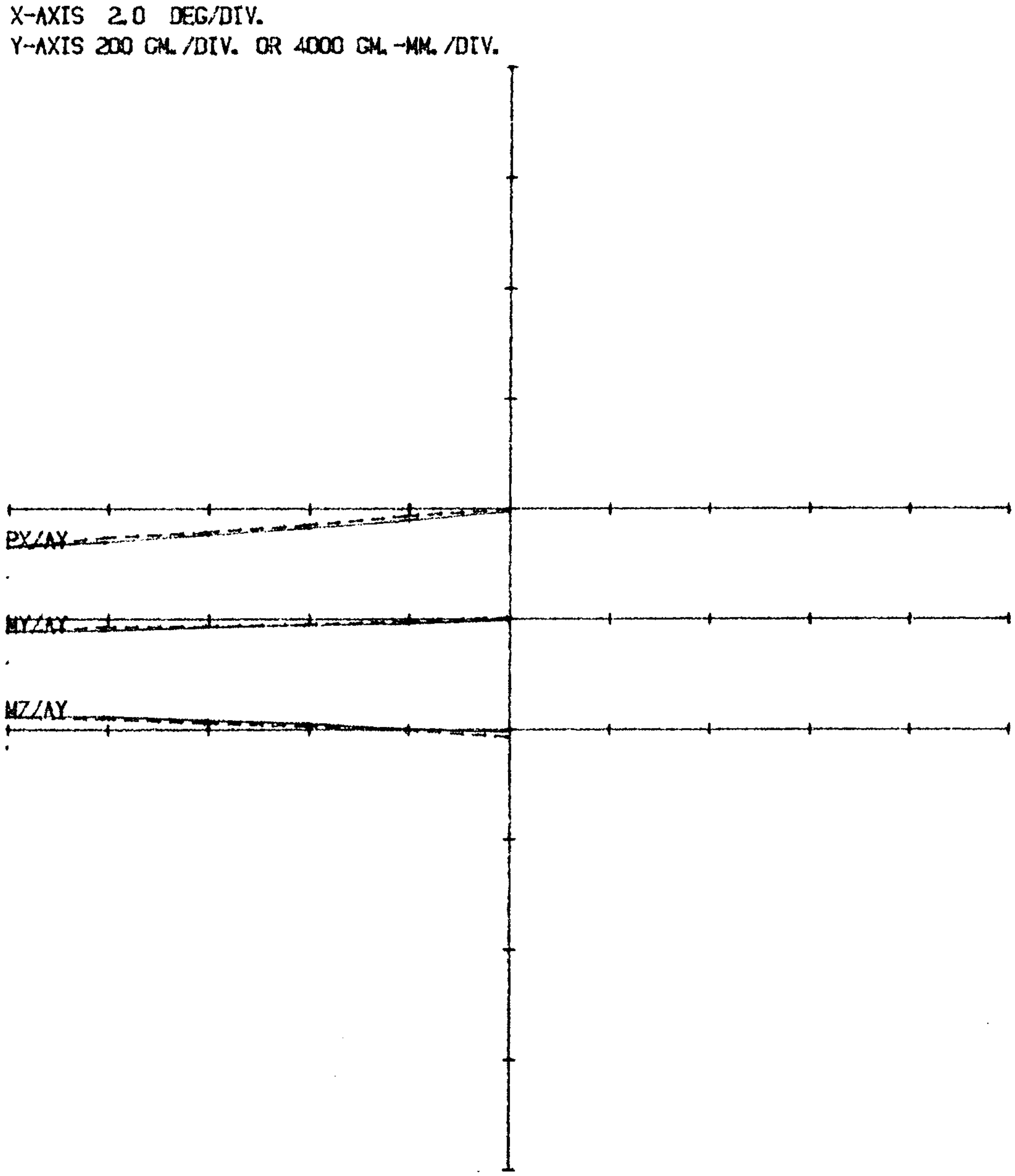

Figure 16: .406 mm (.016 inch) Nitinol - negative activation

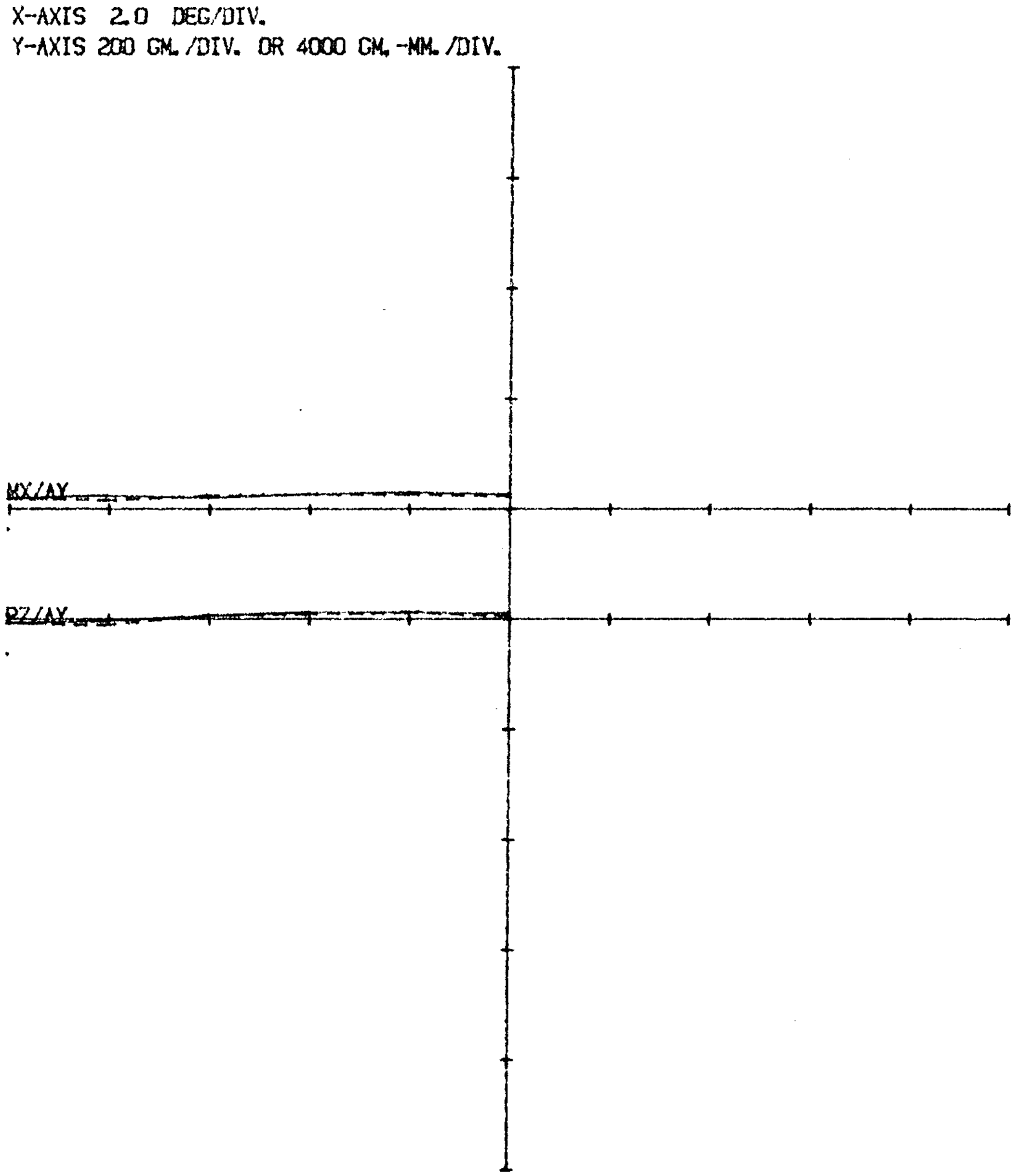

Figure 17: .406 mm (.016 inch) Nitinol - negative activation

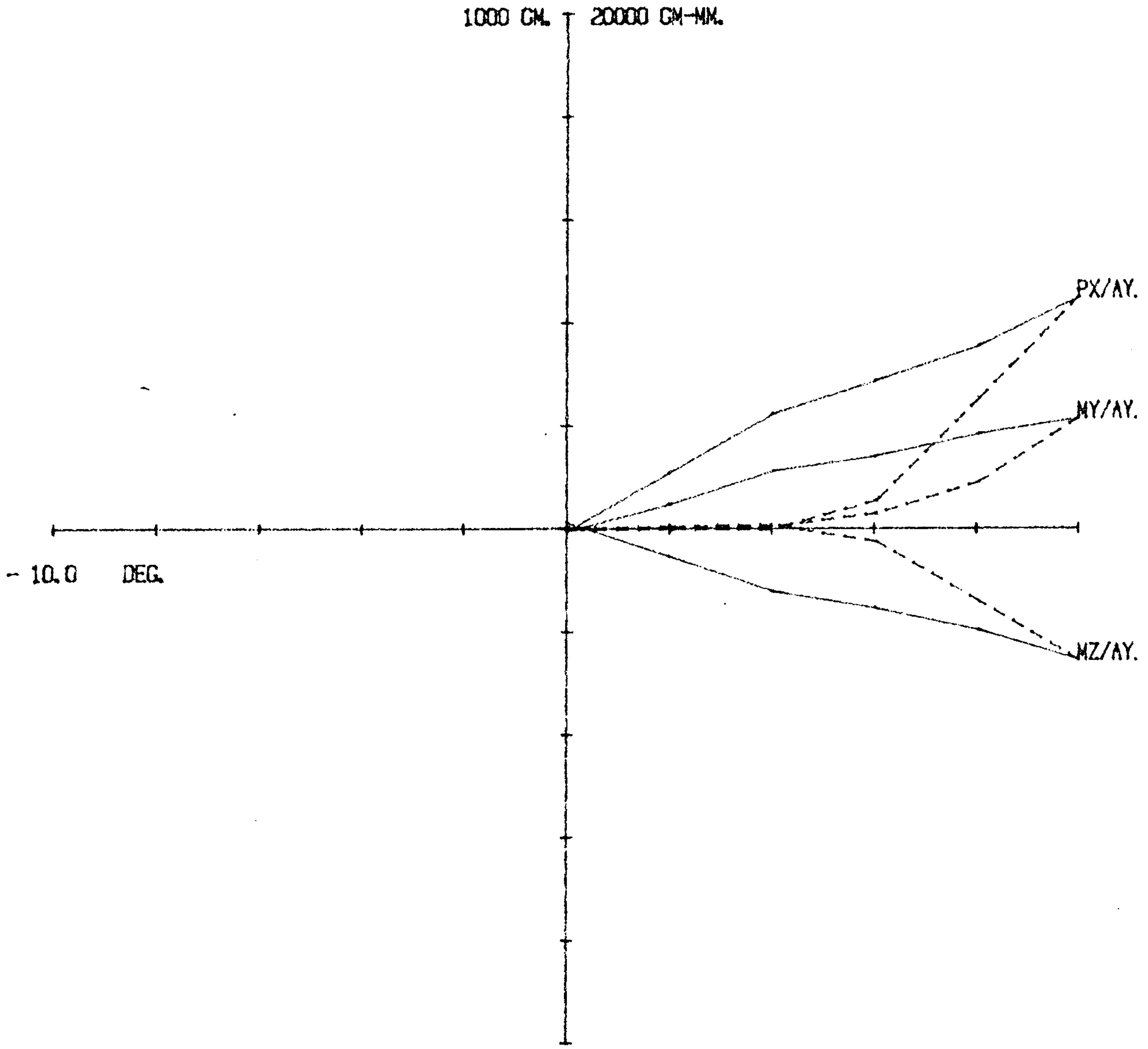

Figure 18: .406 x .559 mm (.016 x .022 inch) stainless steel - positive activation

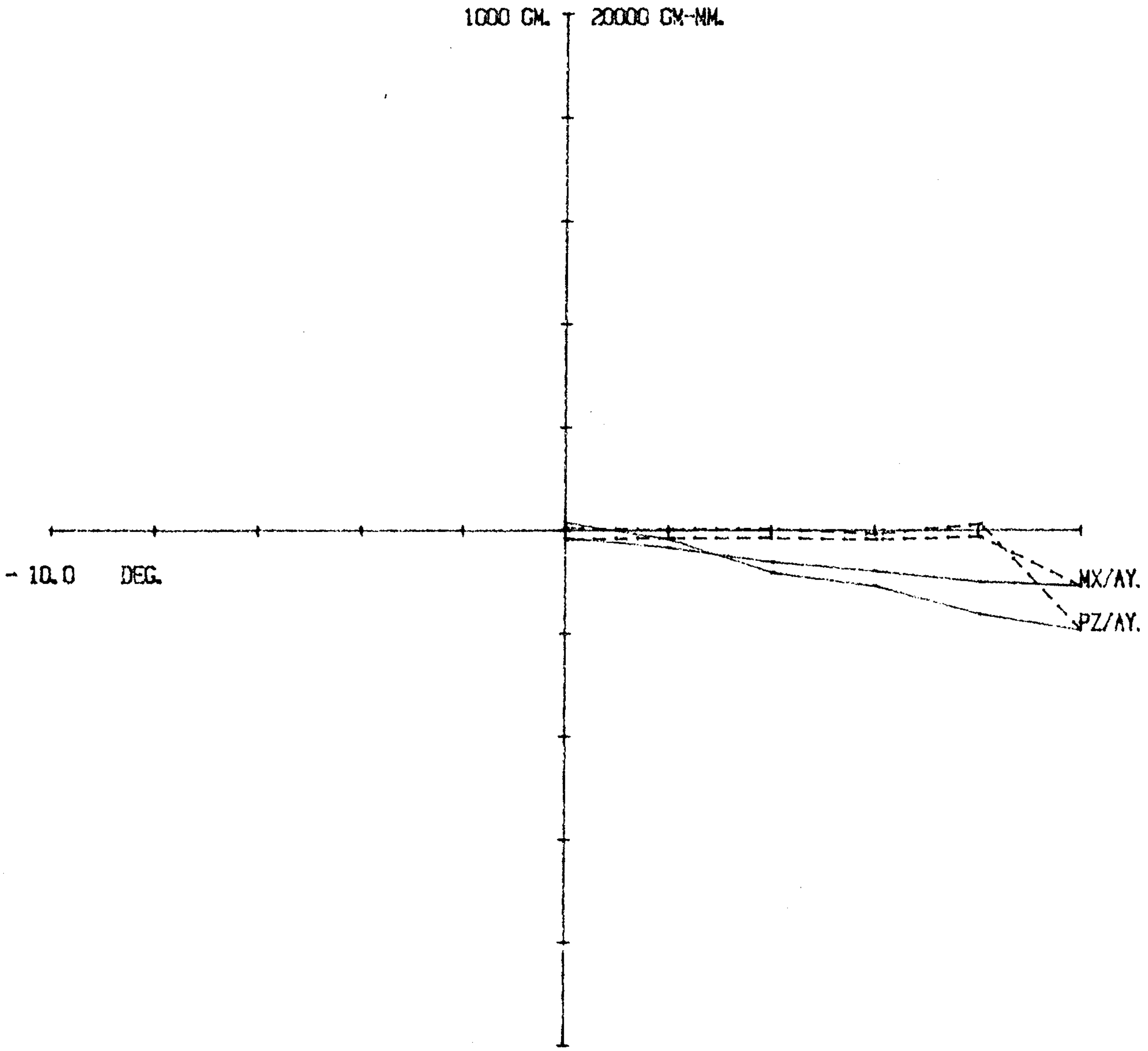

Figure 19: .406 x .559 mm (.016 x .022 inch) stainless steel - positive activation

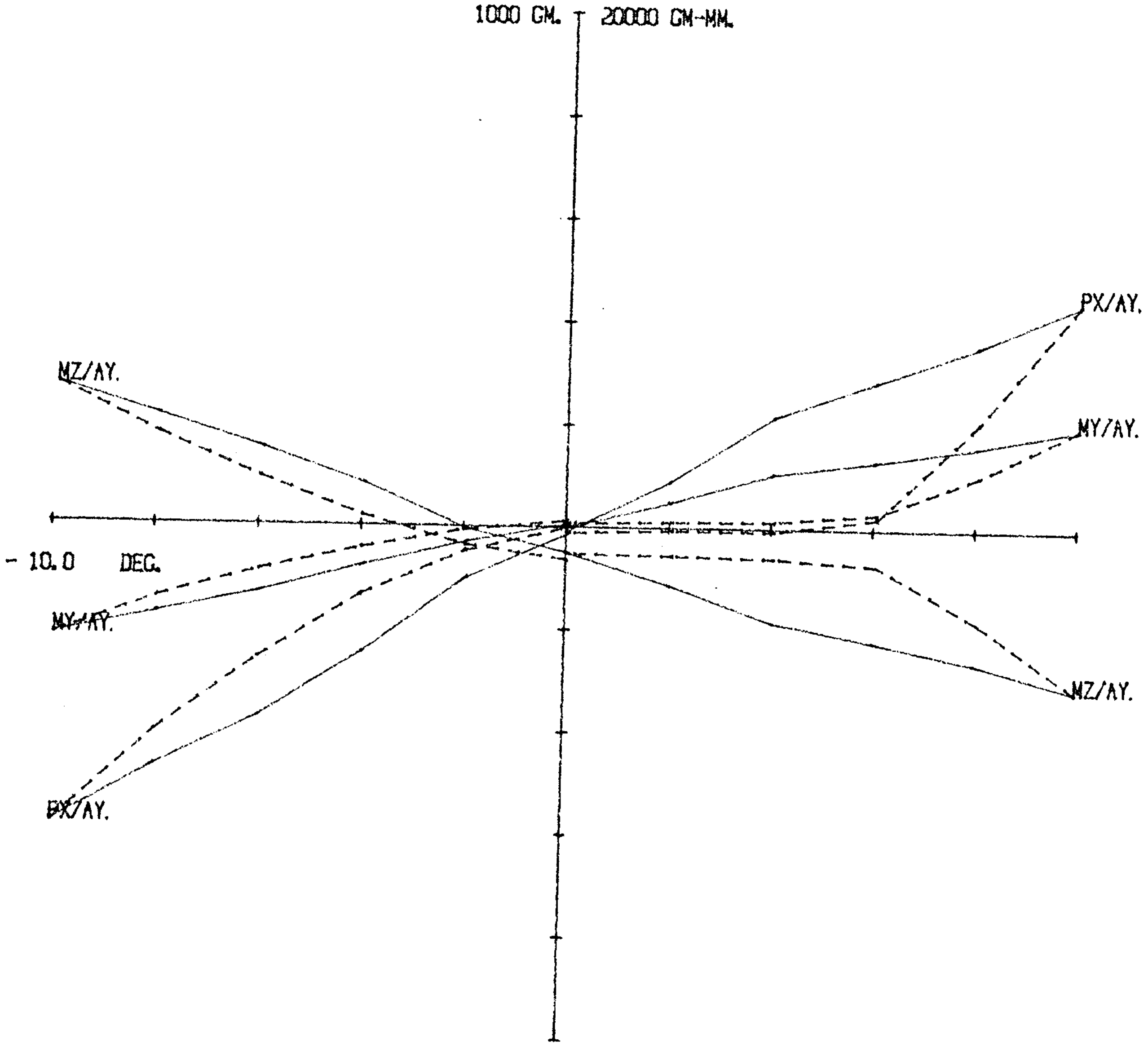

Figure 20: .406 x .559 mm (.016 x .022 inch) stainless steel - initial positive - negative activation cycle

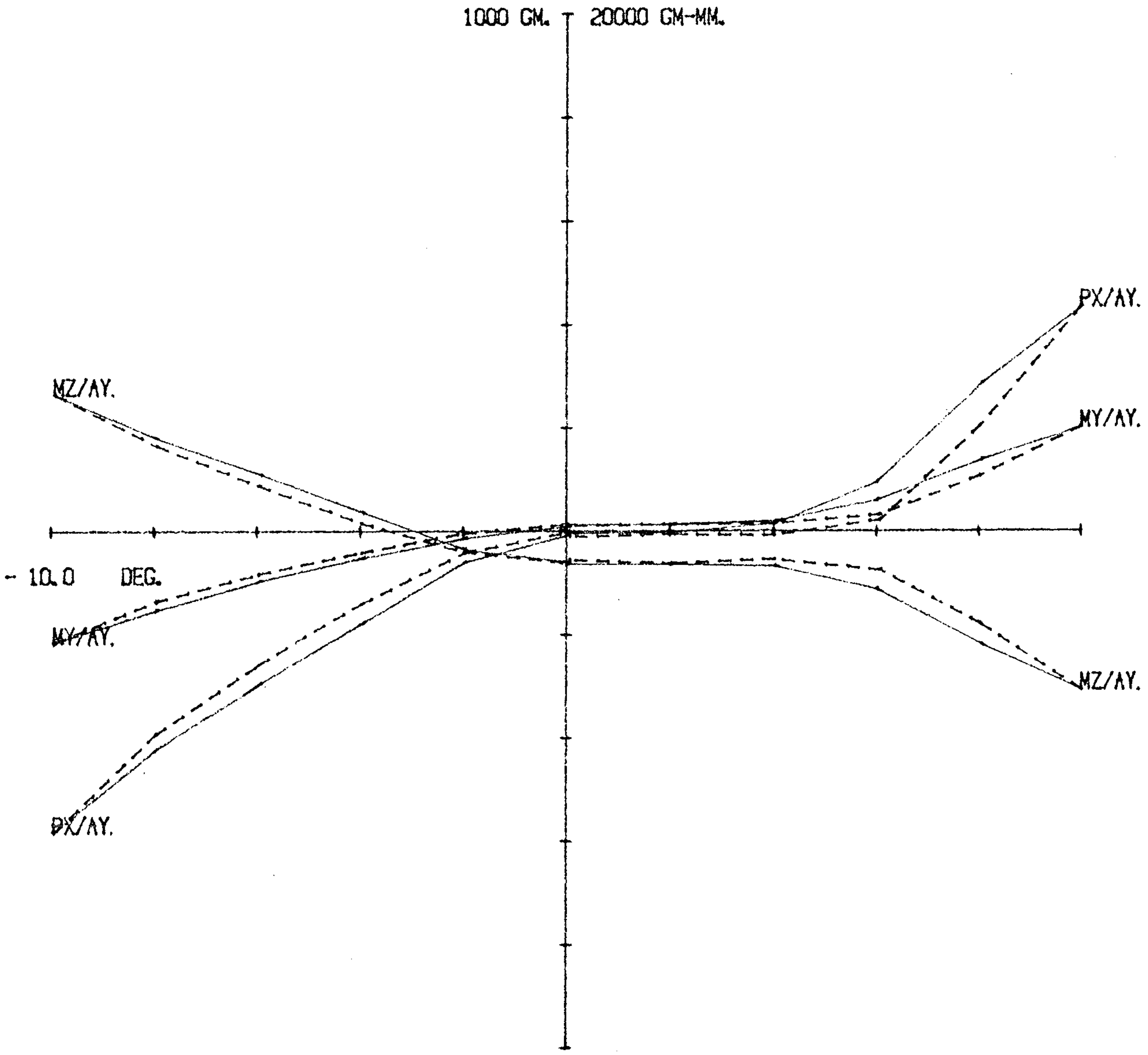

Figure 21: .406 x .559 mm (.016 x .022 inch) stainless steel - second positive - negative activation cycle

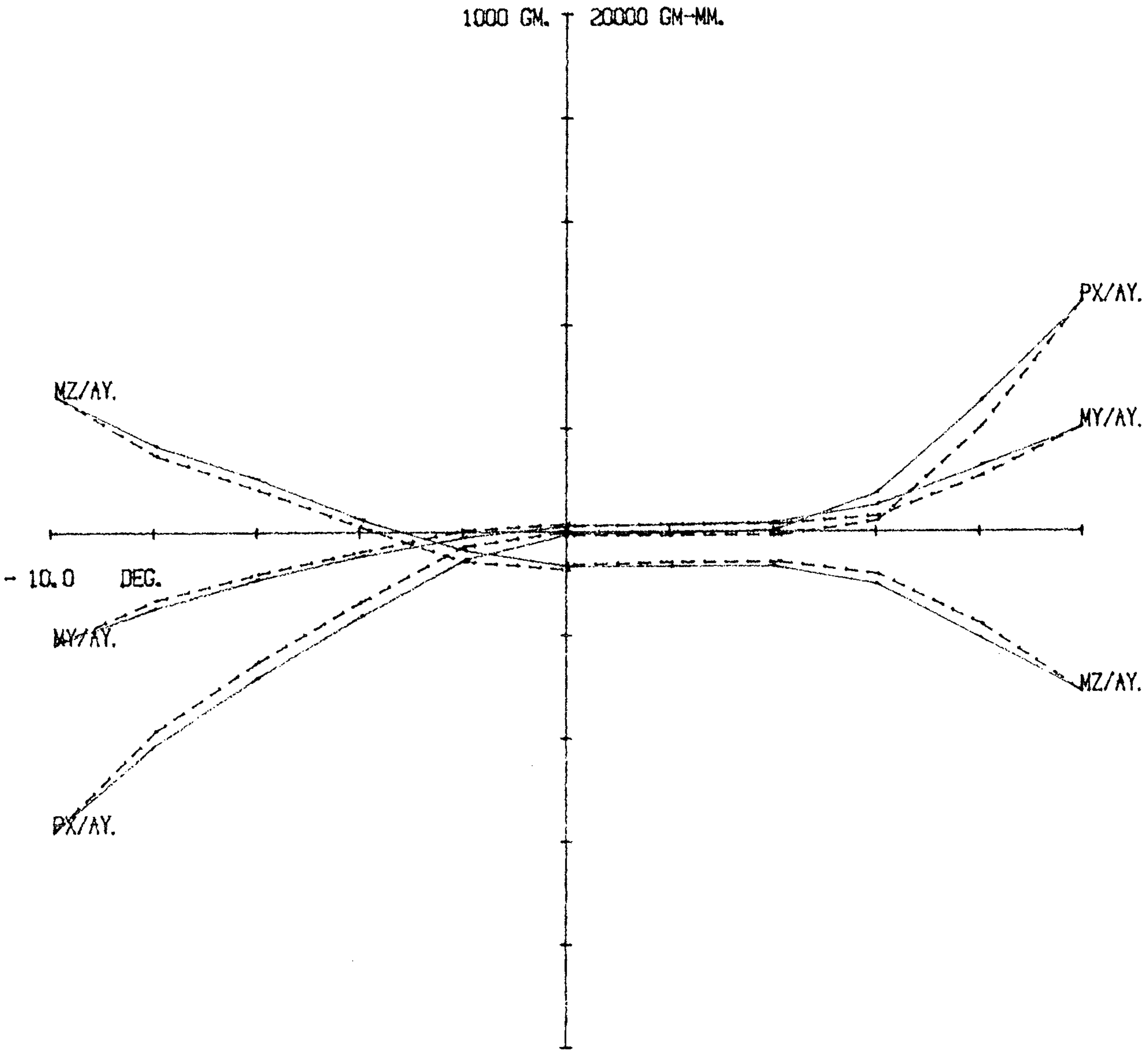

Figure 22: .406 x .559 mm (.016 x .022 inch) stainless steel - third positive - negative activation cycle

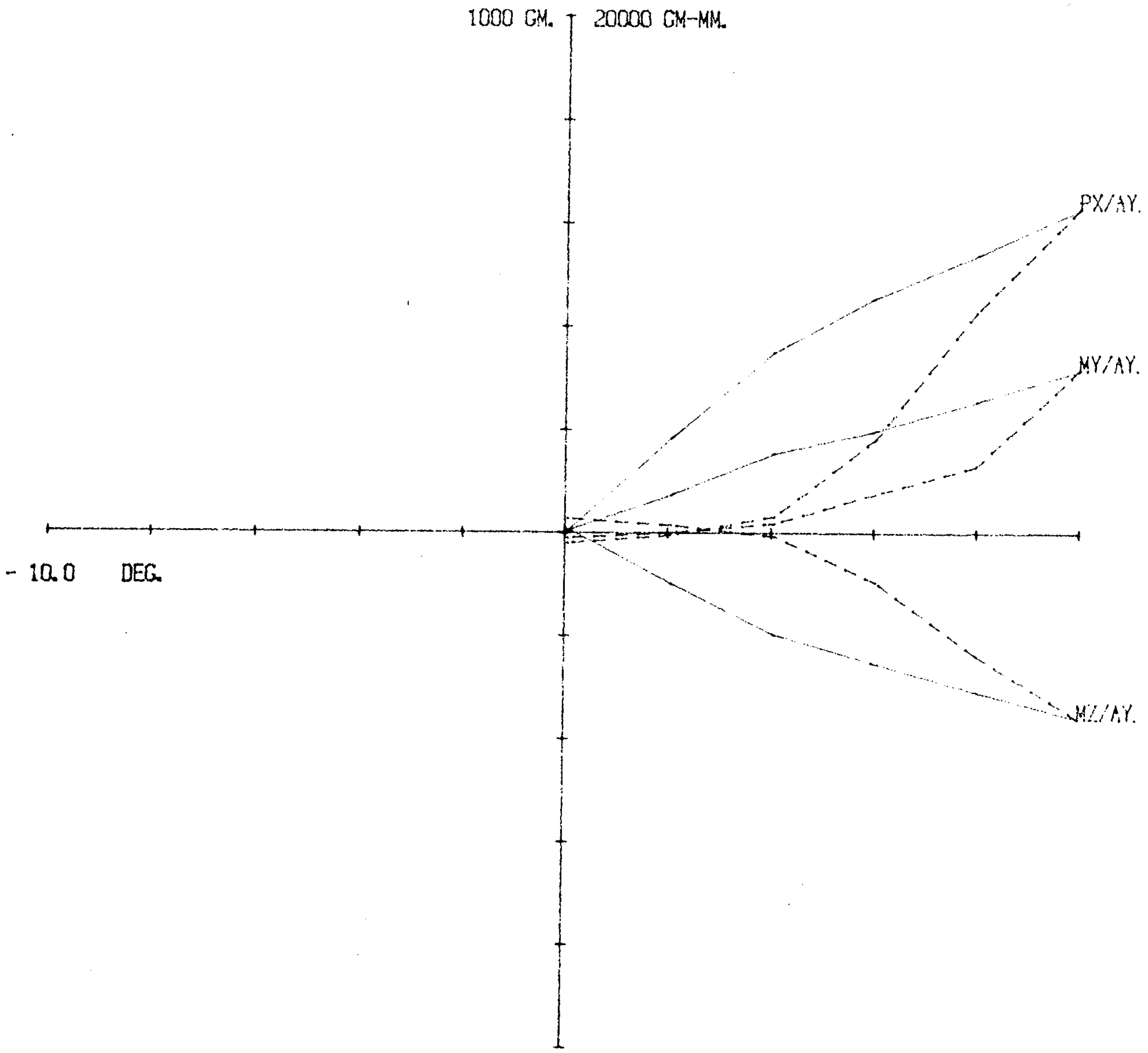

Figure 23: .406 x .559 mm (.016 x .022 inch) stainless steel - .305 mm (.012 inch) ligature - positive activation

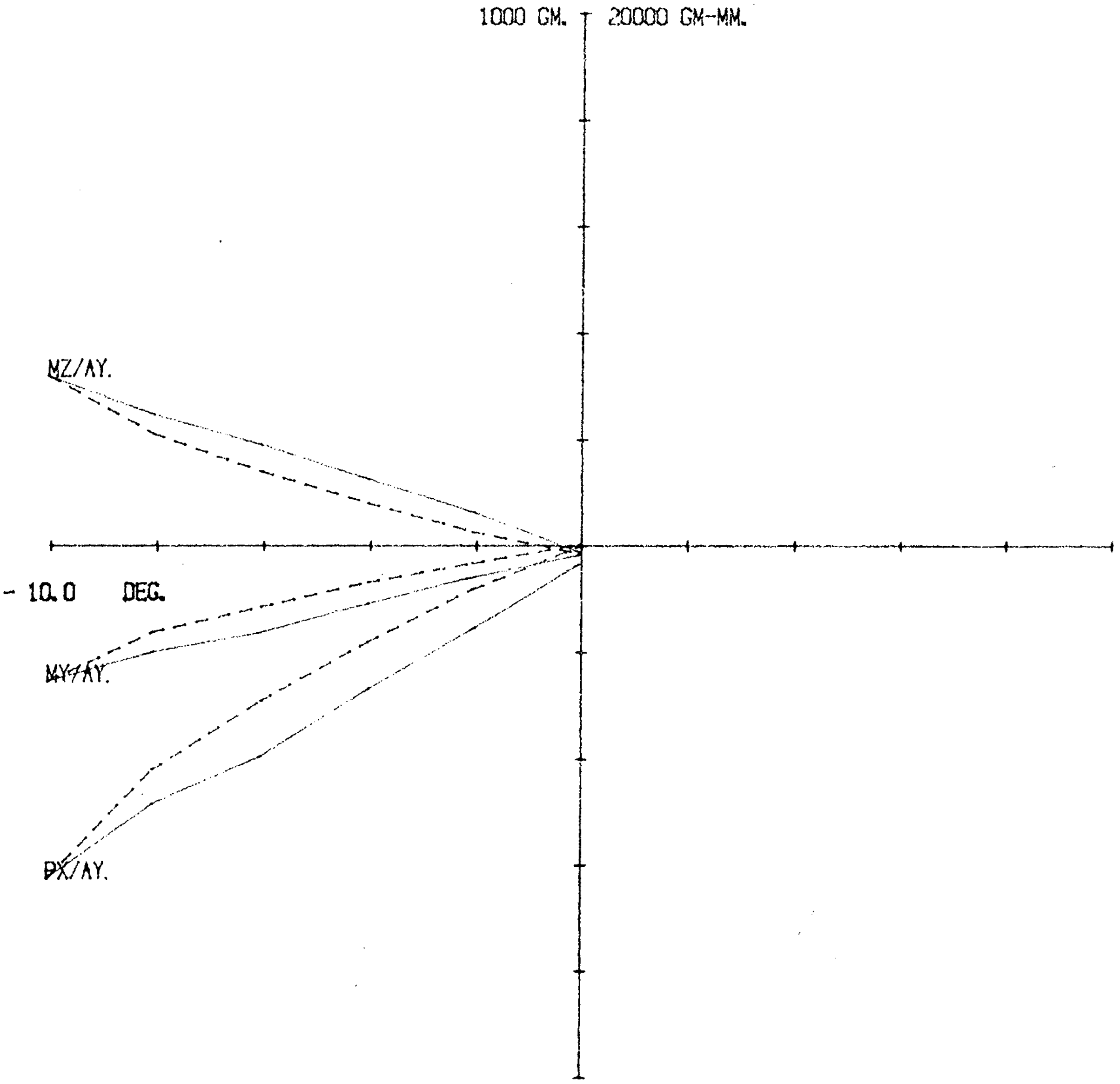

Figure 24: .406 x .559 mm (.016 x .022 inch) stainless steel - negative - activation

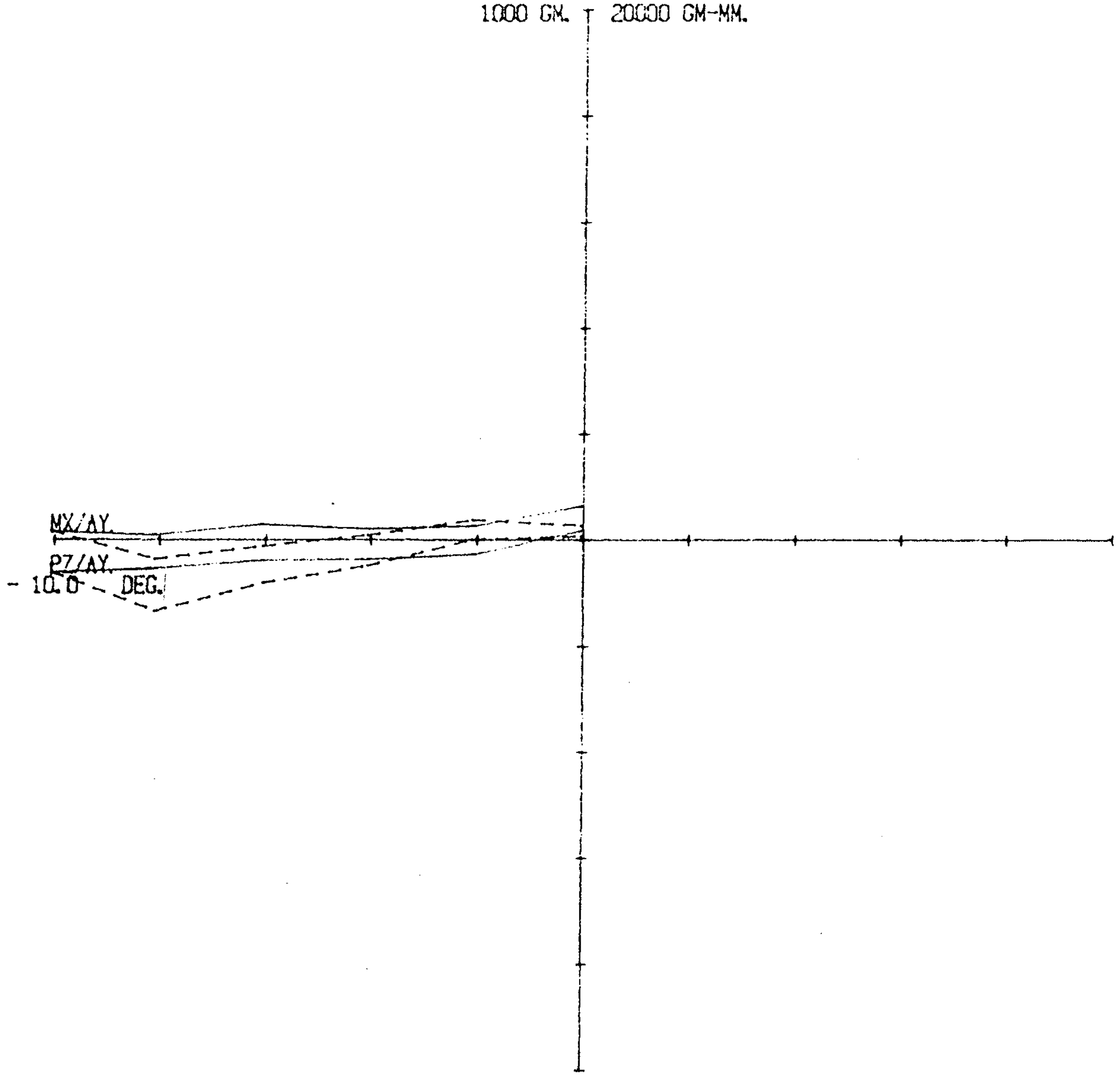

Figure 25: .406 x .559 mm (.016 x .022 inch) stainless steel - negative activation

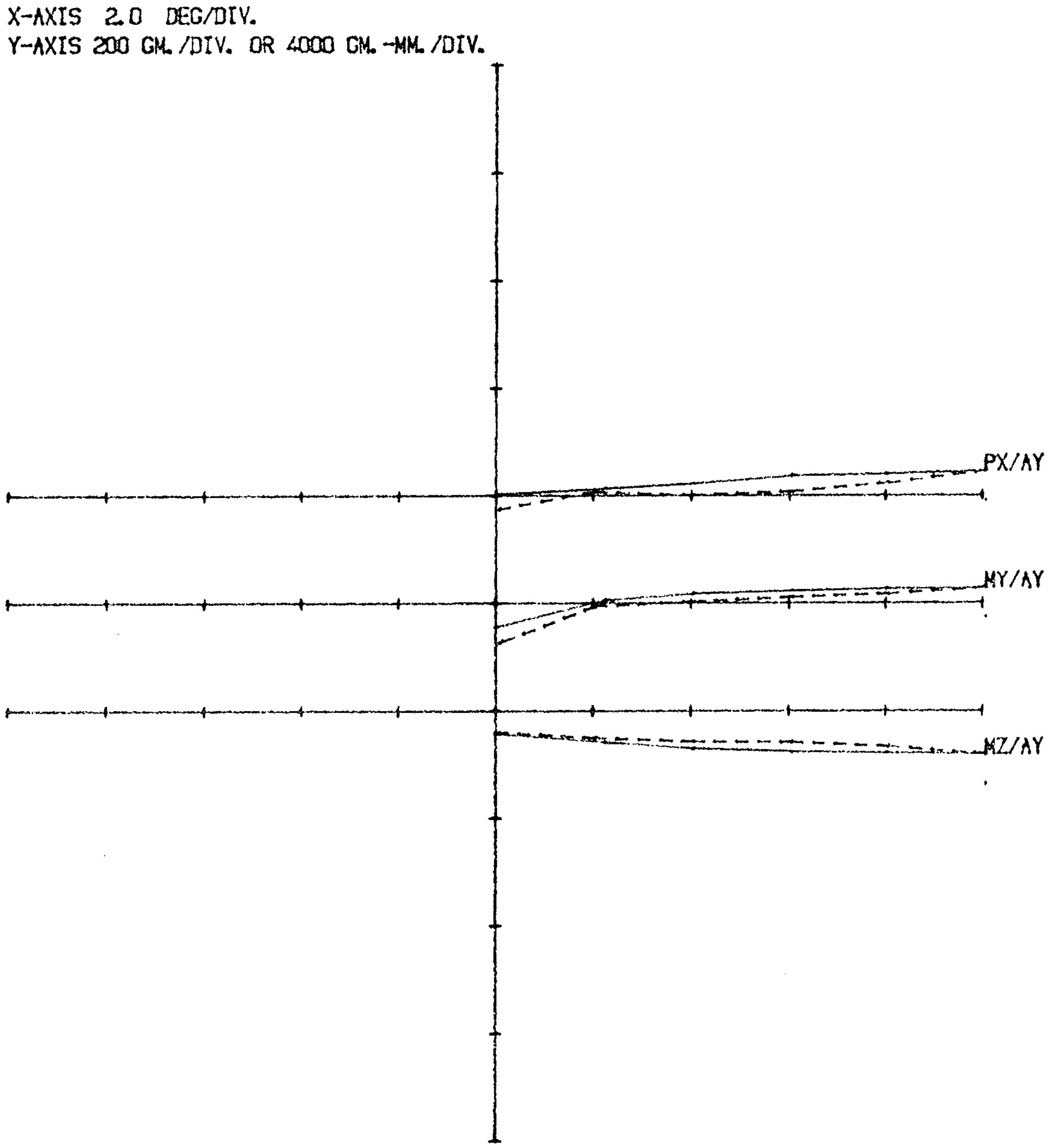

Figure 26: .406 mm (.016 inch) Nitinol - figure-of-eight tie - positive activation

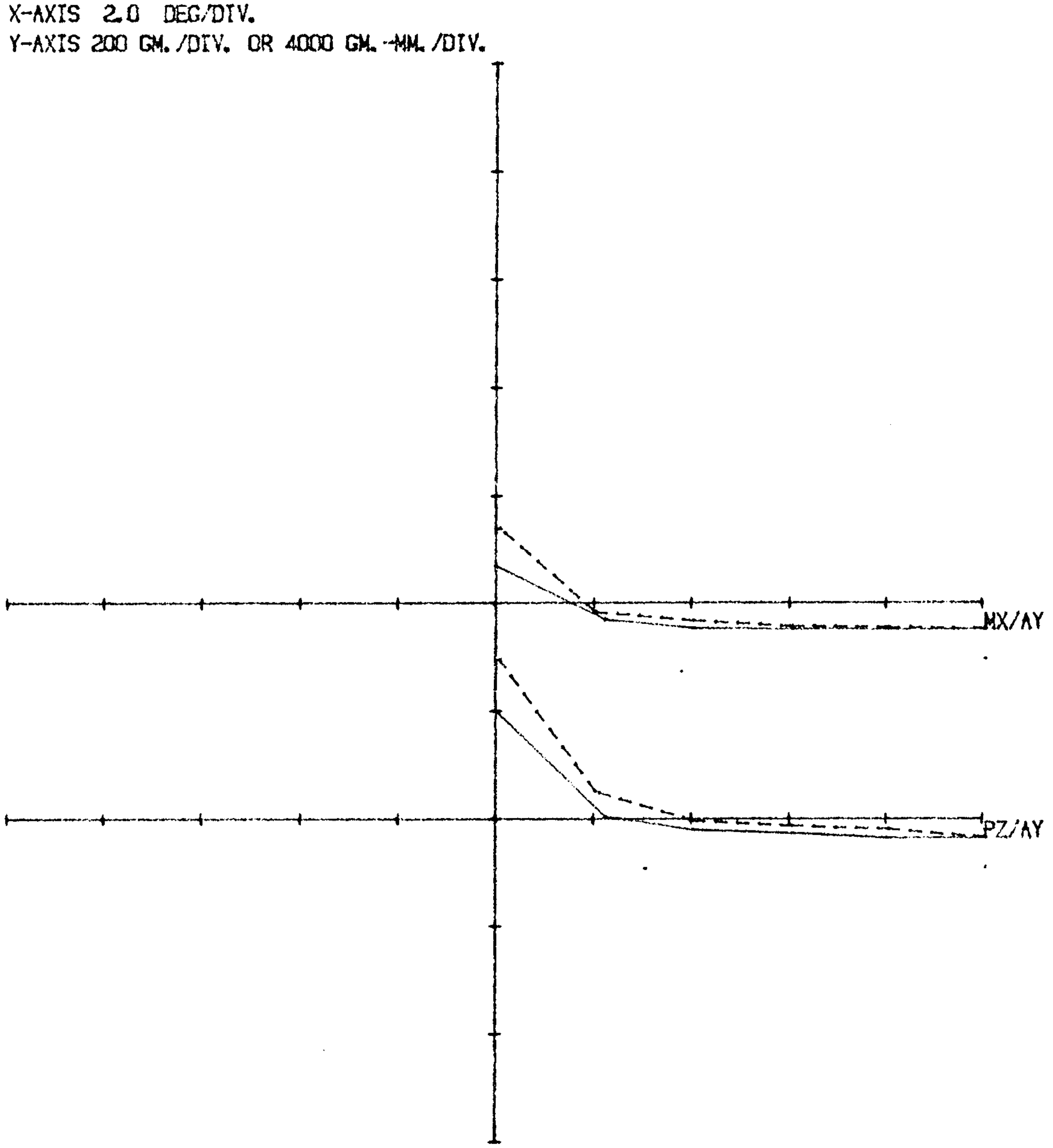

Figure 27: .406 mm (.016 inch) Nitinol - figure-of-eight tie - positive activation

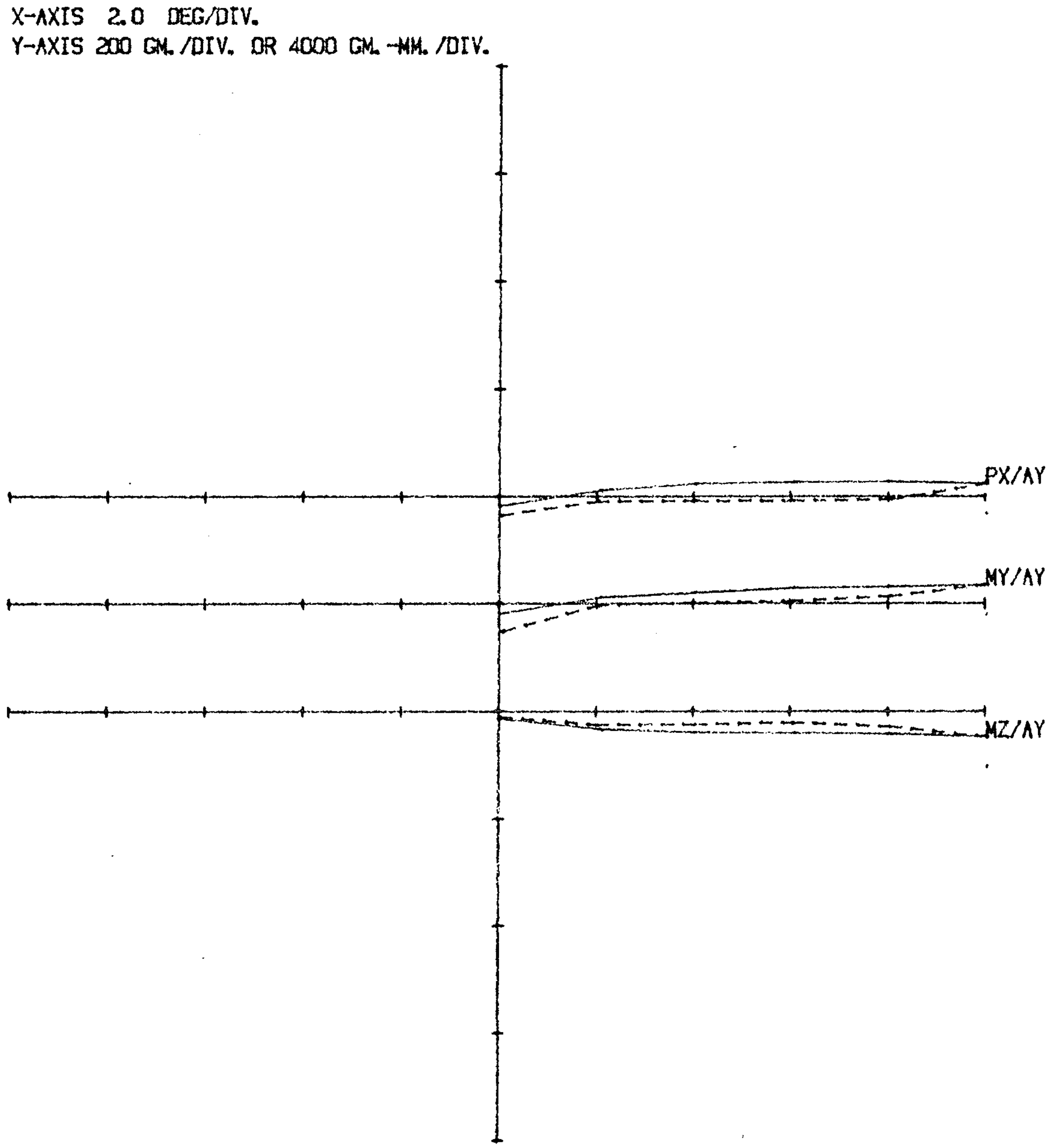

Figure 28: .406 x .559 mm (.016 x .022 inch) stainless steel - figure-of-eight tie - positive activation

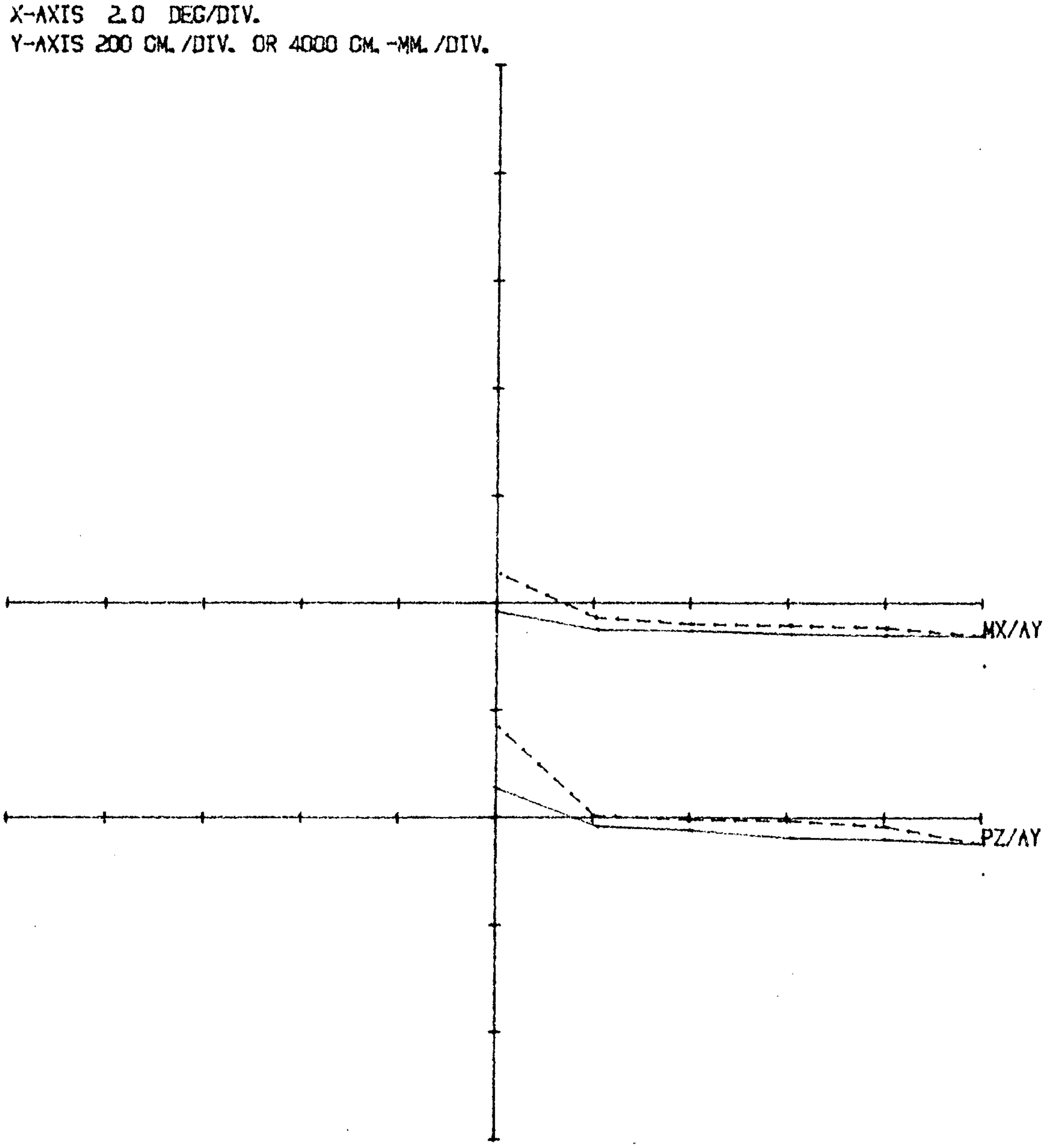

Figure 29: .406 x .559 mm (.016 x .022 inch) stainless steel - figure-of-eight tie - positive activation

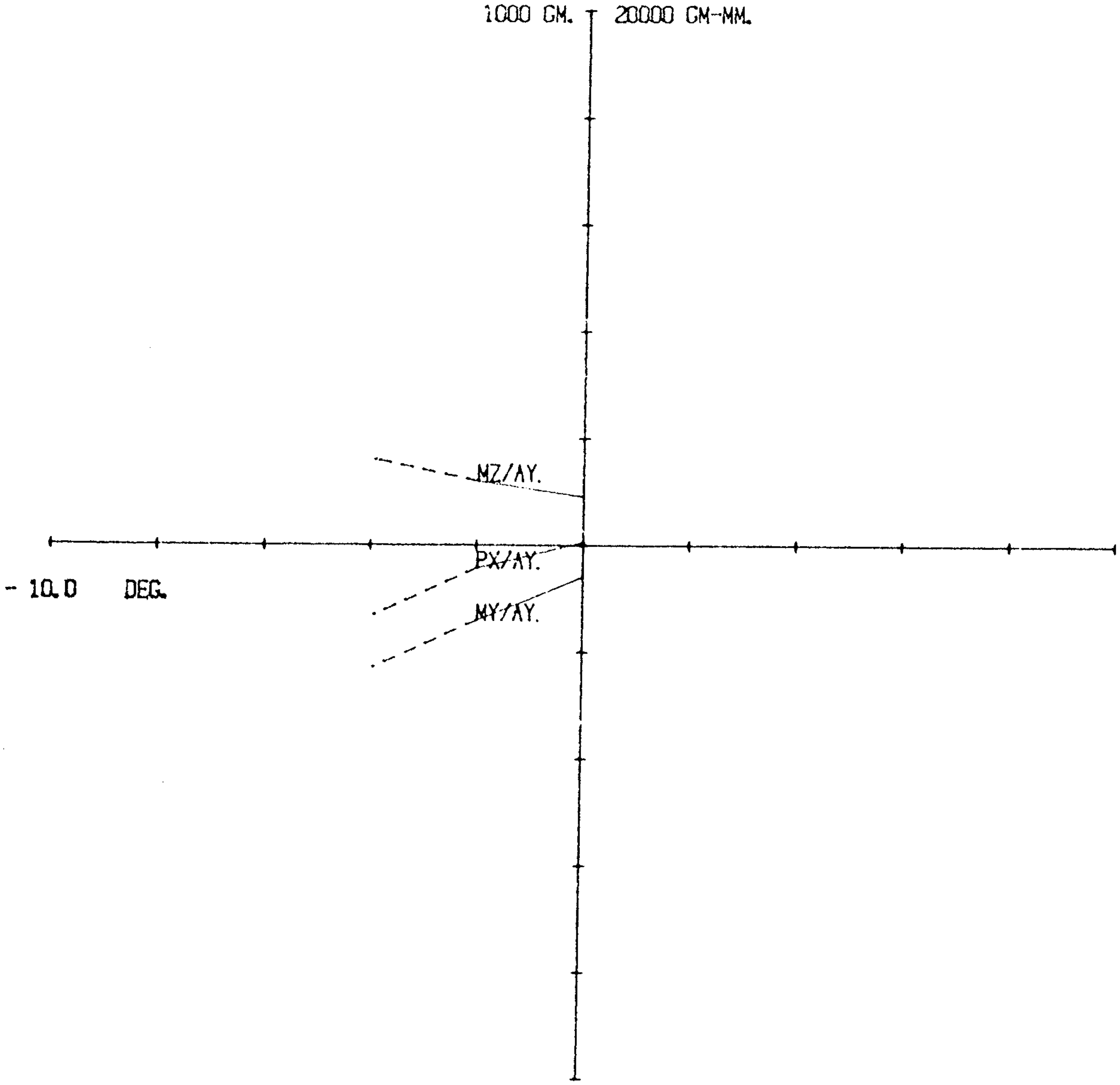

Figure 30: .406 mm (.016 inch) Nitinol - figure of eight tie - negative activation

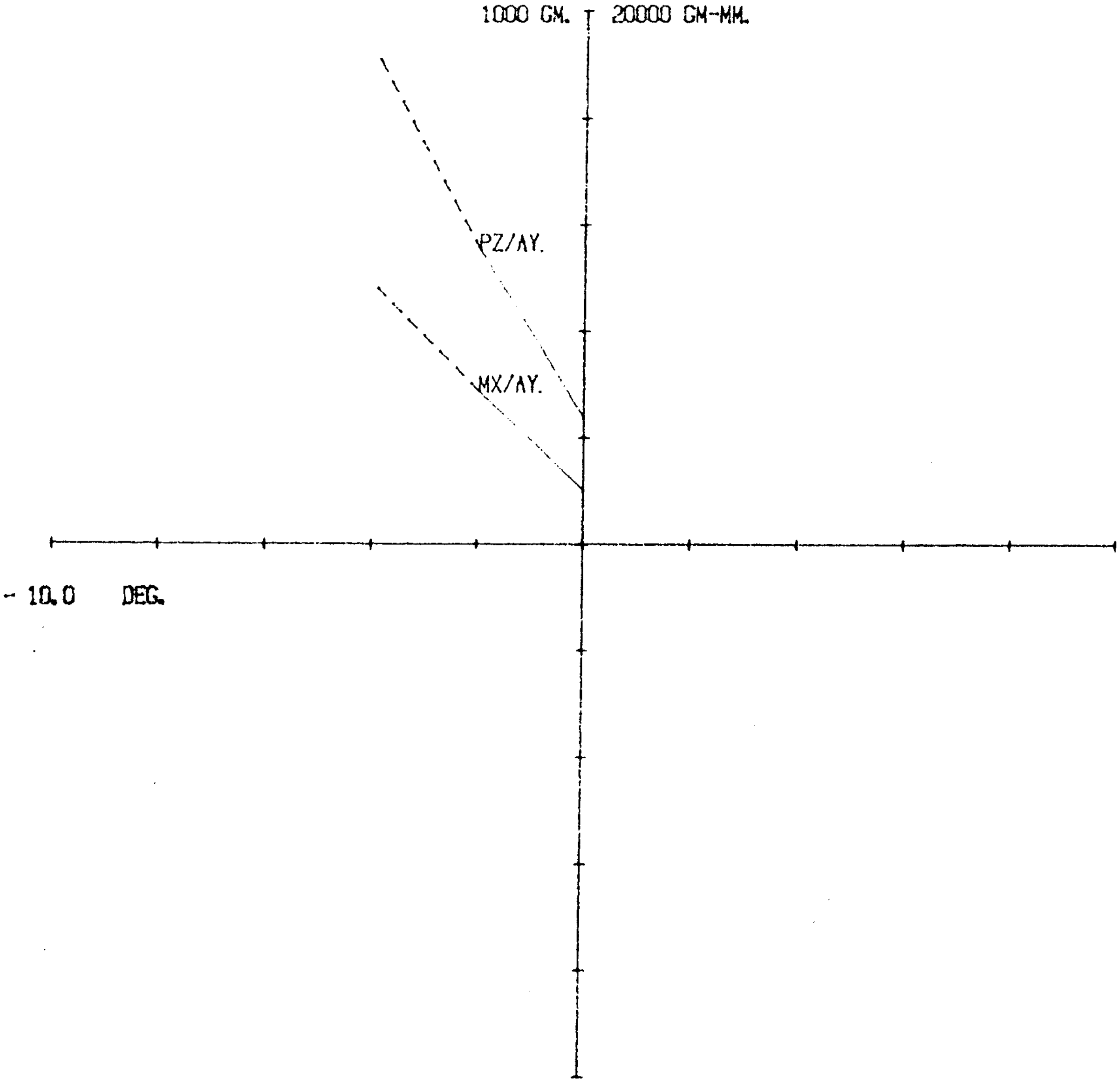

Figure 31: .406 mm (.016 inch) Nitinol - figure of eight tie - negative activation

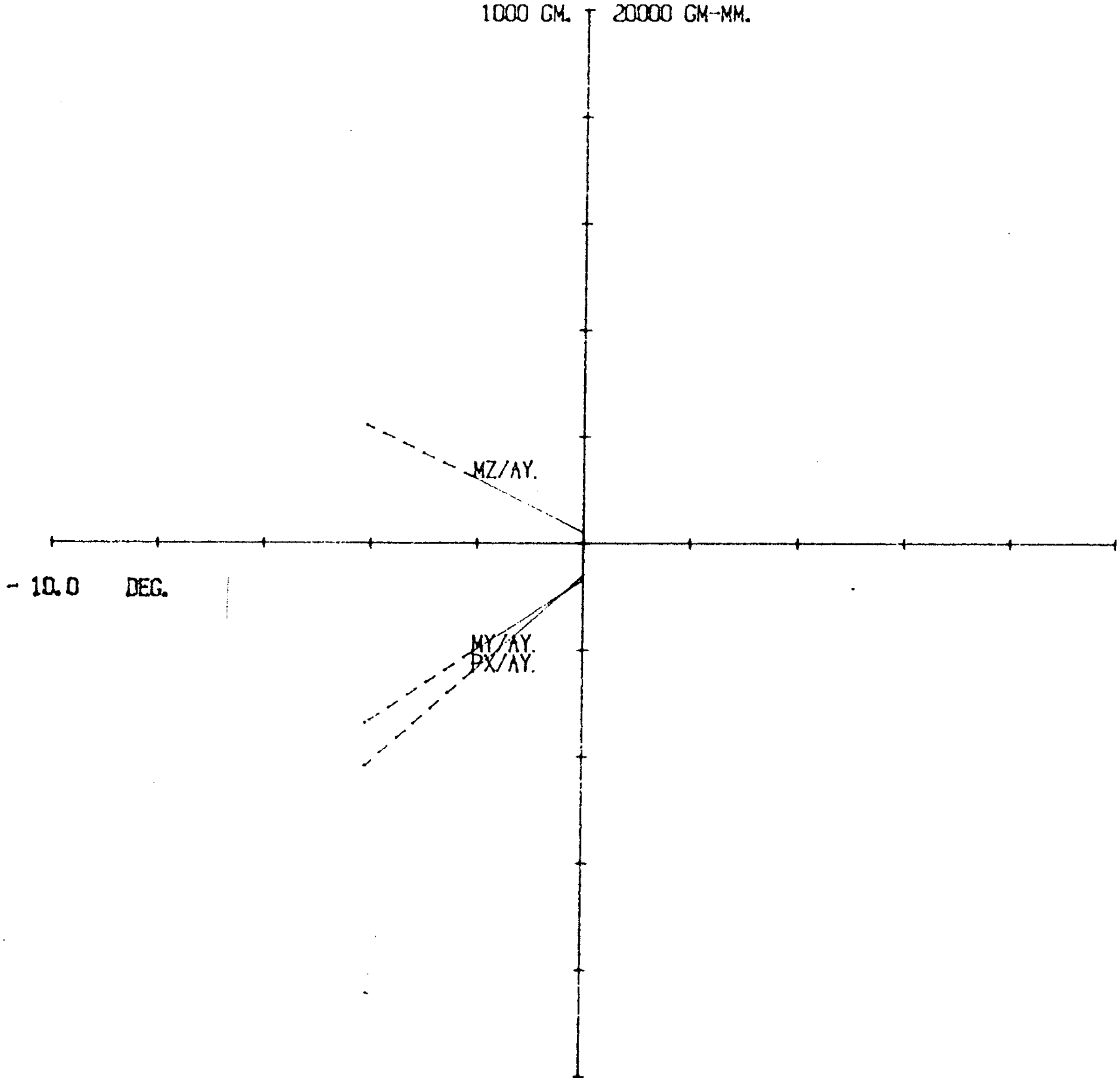

Figure 32: .406 x .559 mm (.016 x .022 inch) stainless steel - figure of eight tie - negative activation

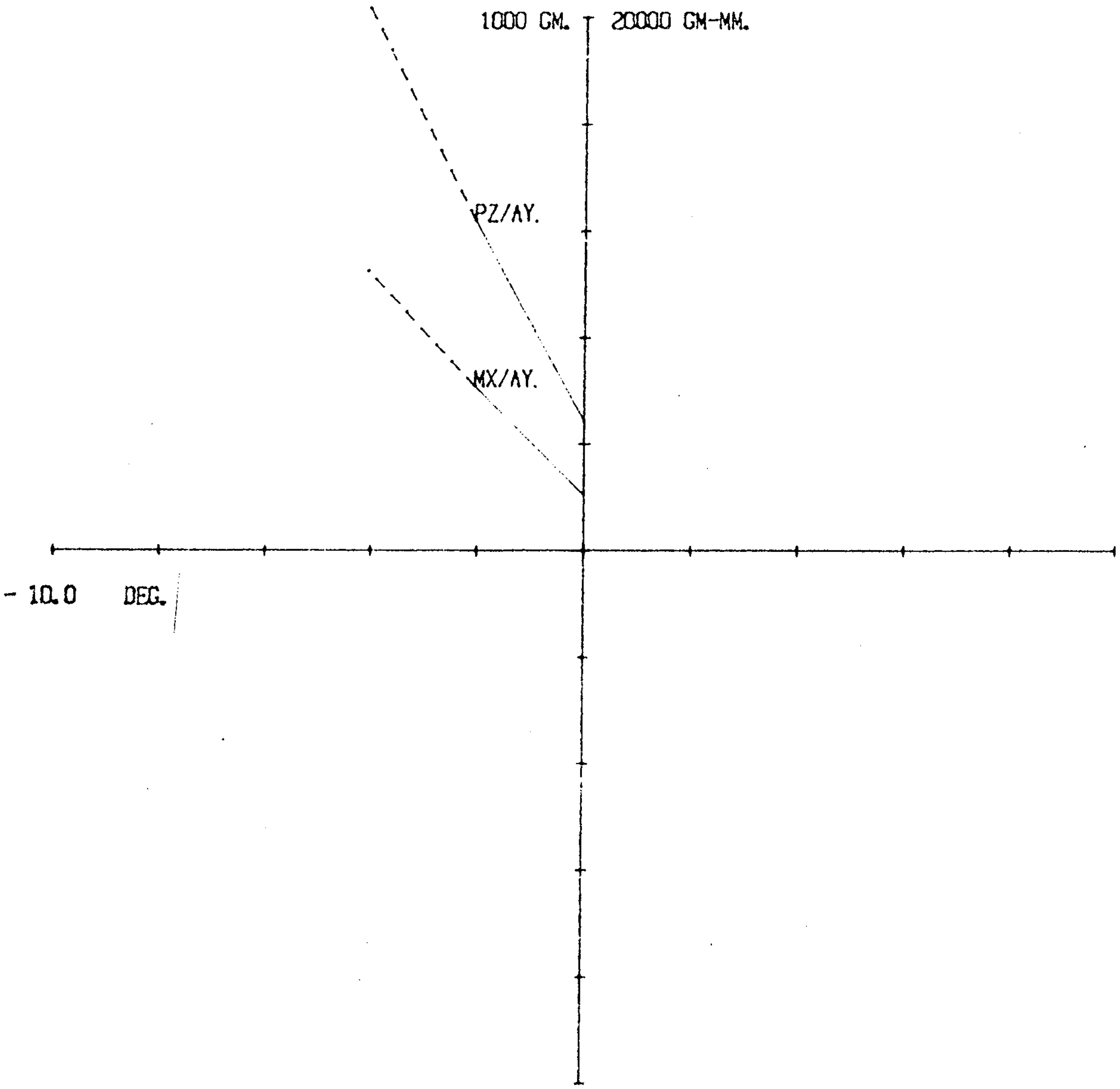

Figure 33: .406 x .559 mm (.016 x .022 inch) stainless steel - figure of eight tie - negative activation

Chapter V

DISCUSSION

It is common in current orthodontic practice to initiate alignment of malposed teeth with low modulus archwires. A previous study (Sullivan, 1982) was done to determine the forces and moments these wires would generate on a malaligned tooth as well as on the FIRST IN LINE anchor tooth.

The present investigation was undertaken to determine how these wires perform in preventing unwanted movement of this anchor tooth. Instrumentation similar to that used by Sullivan (1982) and Levin (1985) was utilized. The apparatus was able to accommodate rectangular wires and hence, comparison between flexible and rigid wires in providing anchorage was possible.

5.1 LOW MODULUS ARCHWIRES

As indicated in Chapter IV, reference to Sullivan's data (1982) will form the basis for anchorage evaluation. His study demonstrated the three dimensional forces and moments on the FIRST IN LINE (F.I.L.) anchor tooth when a flexible wire is used to align a tooth which is displaced 1.5 mm buccally. Readings were taken at three different interbracket distances (I.B.D.), designated as A, B, and C. The I.B.D.'s employed by Sullivan, represent 3 possible relationships between a malaligned tooth, (dotted block - figure 8) and the F.I.L.

tooth of a three tooth anchor segment (solid blocks - figure 8). As specified in section 3.6, the distance between teeth in the anchor segment for this study was kept constant at 6.7 mm (Fig. 4). Table 1

TABLE 1

Selected forces and moments on the F.I.L. tooth at variable I.B.D.
(Sullivan, 1982)

At 2 mm I.B.D. (A)	My = -6000 g-mm. Px = +1000 gm. Pz = +175 gm.
At 3 mm I.B.D. (B)	My = -4000 g-mm. Px = + 600 gm. Pz = + 100 gm.
At 4 mm I.B.D. (C)	My = -2000 g-mm. Px = +290 gm. Pz = +60 gm.

demonstrates the measurements relevant to the present study.

Though absolute comparisons between the former study - in which .508 mm (.020 inch) tubes were used, and this one, employing .457mm (.018 inch) bracket slots - may not be strictly valid, the data provides a resonable reference for comparison.

5.2 POSITIVE ACTIVATION

5.2.1 Rotational Anchorage

Among the primary affects on the FIRST IN LINE tooth coupled to a displaced tooth is a moment about the y-axis (My). Activation as performed in this study, was designed to determine the support the FIRST IN LINE tooth received from two ADJACENT teeth to resist this moment. Figure 14 demonstrates that for a 10 degree activation, the value of My is 1465 g-mm. Reference to Table 1 indicates this would be inadequate to resist rotation at any of the interbracket distances examined by Sullivan (1982). Therefore, for the activations examined in this study, particularly for conditions A and B (table 1), the FIRST IN LINE anchor tooth will rotate in excess of 10 degrees when using flexible archwires.

5.2.2 Linear Control

Rotational (My/Ay) activation on the apparatus results in concomitant generation of forces in the x-direction (Px). Px/Ay indicates the resistance to such force generation, which as figure 14 demonstrates, measures 130 grams for a 10 degree activation. Table 1 indicates that this value for Px/Ay is inadequate to prevent movement of the FIRST IN LINE tooth in the x-direction. Even at condition C (table 1), Px/Ay is about one-half of that required.

This, admittedly, is an indirect assessment of anchorage in the x-direction. Time did not permit a more direct evaluation, which is possible on the present apparatus, and could be accomplished at a future date.

5.2.3 Frictional Effects

Reference to figure 15 indicates that positive activation produces forces along the mesial-distal axis (Pz). This force is most likely attributable to friction, as activation tends to wedge the wire into the bracket of the FIRST IN LINE tooth. This explains the rapid diminution of Pz that occurs with deactivation (hysteresis), which rapidly eliminates the wedging, and hence the friction. Though the magnitude of this force is small, (approximately 100 grams) it appears to be sufficient to resist the Pz force which Sullivan demonstrated, and suggested would 'jiggle' the FIRST IN LINE tooth, as the primary reciprocal effects were played out. Of interest is that a force in the z-direction (Pz) would tend to oppose rotation of the tooth caused by My. Comparison of Pz/Ay with My/Ay shows that the plots follow a very similar but inverse pattern, including the hysteresis that occurs with deactivation. This indicates that the frictional force is likely contributing to what little rotational control there is.

5.3 NEGATIVE ACTIVATION

Analysis of the plot My/Ay for a negative activation (Fig. 16) indicates that resistance to rotation is essentially non-existant. In this situation, activation rotates the ADJACENT teeth away from the FIRST IN LINE tooth. Hence, the frictional effect (reflected by Pz, Fig. 17) does not occur, resulting in even less support in all directions than for positive activation.

The results indicate that with light wires, bending stiffness is insufficient to provide adequate anchorage. However, resistance to a force in the z-direction, and, to a small degree to an My moment, is modified by a differential frictional effect, which depends on the direction of the reactive moment on the FIRST IN LINE tooth. This is turn, depends on whether the FIRST IN LINE tooth is coupled to a buccally or lingually displaced tooth. Positive activation represents the case where the FIRST IN LINE tooth is coupled to a tooth which is buccally displaced. The reactive moment on the FIRST IN LINE tooth produces the frictional effect, which provides adequate anchorage against Pz forces (table 1, conditions B and C), and some (though inadequate) measure of anchorage against an My moment. Negative activation represents the FIRST IN LINE tooth coupled to a lingually displaced tooth, where the reactive moment does not produce a frictional effect and, hence, not even mesial-distal 'jiggling' is prevented.

The above results are based on the parameters established for this investigation, which are, to examine anchorage primarily as a function of the properties of the wire. Therefore, under the conditions examined, it is apparent that the FIRST IN LINE tooth of a three tooth anchor segment will receive insufficient support from two ADJACENT teeth to prevent rotation about the y-axis or movement in the x-direction. Though resistance to mesial-distal 'jiggling' likely occurs in some instances, it is variable and only a minor component of the stability required.

However, the effect of such factors as:

1. interbracket distance

2. ligation
3. and slot size

must be considered before the complete picture is known.

For example, the present study employed an interbracket distance of 6.7 mm, which is most representative of the situation in the molar region. In the bicuspid, and especially in the lower incisor region, interbracket distances would be appreciably shorter. Since stiffness varies inversely with the cube of the length, the stiffness of the wire in these regions would be appreciably higher. The result may be a more rigid connection between anchor teeth, with less potential movement of the FIRST IN LINE tooth.

The ligation technique would also be a factor. Rigid constraint between brackets with stainless steel ligatures increases the effective stiffness of the wire between those brackets. As such, a malaligned tooth ligated with elastic ligature, coupled to an anchor segment in which all teeth are constrained with stainless steel ligatures may help prevent anchor tooth movement. However, caution must be exercised, particularly with short interbracket distances, as plastic deformation of the archwire may occur between the malaligned and FIRST IN LINE anchor tooth (Sullivan, 1982).

A third consideration would be slot size. Larger slots allow more 'play' between the wire and the slot, and would decrease the reciprocal forces and moments acting on the FIRST IN LINE tooth (Sullivan, 1982). However, this may be offset by the increase in play between the wire and the slot that would also occur in the anchor segment. Therefore, though the FIRST IN LINE tooth may be subject to lower reciprocal forces and moments with increased slot size, the anchor segment would be correspondingly less rigid. The overall effect may therefore not vary significantly from that observed in this study.

5.4 RECTANGULAR WIRE

Traditional concepts of intramaxillary anchorage involve 'binding' segments of teeth with rigid rectangular wire. It is felt that rectangular wire is sufficiently stiff to resist bending when a force is placed on any tooth supported by that wire. The present study sought to examine this contention by studying .406 x .559 mm (.016 x .022 inch) stainless steel rectangular wire in the manner used to examine low modulus wires. Though these wires are not used for initial alignment, they are no doubt required to provide rotational resistance under normal clinical conditions.

5.5 POSITIVE ACTIVATION

The difference in wire stiffness between .406 mm (.016 inch) Nitinol and .406 x .559 mm (.016 x .022 inch) stainless steel is substantial (66.56 vs. 1129.79, Burstone and Goldberg, 1981). This would lead one to expect large My/Ay values indicative of good support. However, examination of figure 18 reveals that the slope of My/Ay begins to level off following 4 degrees of activation. A decrease in the value of My/Ay due to wire flexibility would exhibit a deactivation plot which more closely resembles that of activation. However, deactivation exhibits a considerable degree of hysteresis (notwithstanding the effect of Pz), indicating that permanent deformation had occurred somewhere in the set-up. Examination of the wire revealed no deformation, leaving the ligature as the only source.

As indicated in Chapter IV this speculation was tested by repeated cycles of positive and negative activations. The initial deformation occurs during the first cycle of activations (Fig. 20). The plots following this first cycle (Fig. 21 & 22) show that the slopes of the force and moment plots remain nearly zero over the first 6 degrees of positive activation. This indicates markedly decreased restraint of the wire in the bracket of the FIRST IN LINE tooth. Only after the tooth has rotated sufficiently (slightly in excess of 6 degrees) to again engage the permanently deformed ligature, do plot values begin to increase.

Figure 23 demonstrates the effect of increasing the ligature size to .305 mm (.012 inch). This represents a 100% increase in stiffness of the ligature. The plot for My/Ay shows approximately a 60% increase over that seen in Figure 18. However, the deactivation plot demonstrates the same pattern of hysteresis as obtained with the .254 mm (.010 inch) ligature, indicating that deformation of the ligature is due primarily to the rectangular wire exceeding the bending stiffness of the ligature, but also involves the sharp edge of the wire 'gouging' the ligature surface.

The results lead to interesting speculation regarding variable modulus orthodontics as advocated by Burstone (1981). The technique recommends using full dimension rectangular wires earlier in treatment. This is possible by using a wire with a modulus of elasticity lower than that of stainless steel (i.e. T.M.A., Burstone & Goldberg, 1980). Burstone believes this leads to earlier torsional and hence, earlier overall control of tooth position. However, it is possible that the sharp edge of the rectangular T.M.A. may also cause ligature deformation. It might be argued that since these wires are less stiff than stainless steel, the propensity to deform the ligature would be less. However, T.M.A. is normally deflected over larger distances than stainless steel. This increased deflection of the wire might result in it contacting the ligature with sufficient force to cause deformation.

5.6 NEGATIVE ACTIVATION

The results for reverse activations (Fig. 24 & 25) are similar to those obtained for positive activations. Notable however, was a moderate decrease in hysteresis with deactivation. Two explanations were thought to account for this. One, being the reduced Pz forces. As noted above, Pz contributes to deactivation hysteresis. Secondly, reverse activation causes the wire to contact the ligature at the pigtail tie. Since more wire is incorporated on the side of the tie, it was speculated to be potentially more resistant to deformation. Accordingly, reversing the side on which the pigtail is tied, should alter both the support and the hysteresis observed.

The results obtained with this modification in technique (Appendix, Figures 9 & 10), show only minor variations from those demonstrated in figure 24, indicating that the pigtail does not offer any greater resistance to deformation. Hence, the side on which the ligature is tied appears not to alter support appreciably. This may be due to inability to tie the ligature with identical tension at every trial, thereby eliminating any potential benefit derived from tying on the side of the bracket where the wire will contact the ligature.

The results obtained with rectangular wire indicate that exception may be taken to the long held belief that 'connecting' teeth with large rectangular wires prevents any appreciable relative movement in the anchor segment. Reciprocal forces on the FIRST IN LINE tooth in an anchor segment which cause the wire to make forceful contact with the ligature, will likely result in the wire no longer remaining fully engaged within the bracket, as it progressively deforms the ligature. As such, considering the indeterminancy of forces and moments acting on individual teeth with continuous arches, (Steiner 1932, Burstone 1962) the clinician is well advised to ensure that the wire has remained <u>fully</u> engaged in the brackets of all teeth at all appointments subsequent to implementing rectangular arches.

Clinically, the occurance of ligature deformation may present itself in two forms. One, being, where a heavy force is required to engage the rectangular wire in the slot. Normally, as the force on the wire acts out, the tooth moves with it. However, the above cited results indicate that as the wire moves, the ability of the ligature to keep it in the slot may be exceeded, resulting in less than full wire engagement.

Secondly, attempting to engage a rectangular wire in a slot by tightening the ligature around it can lead to deformation, as the force required to seat it exceeds the bending stiffness of the ligature. In both cases control of tooth movement is reduced by virtue of reduced wire engagement in the slot.

Recent modifications in bracket design include those in which wires are secured without ligatures. A metal 'snap' is employed to secure the wire in place. These brackets would potentially eliminate the 'weak link' in the system when using rectangular wires. However, such brackets would be disadvantageous in that they would prevent one from employing a differential constraint factor (i.e. tight vs. loose ligation) when this may be advantageous, and hence, might result in placing bigger loads on the anchor segment than occurs with tied ligatures. These brackets would also eliminate the ability to ligate solely to the mesial or distal wing when correcting severe rotations.

5.7 SPECIAL LIGATION

Figures 26 & 27 demonstrate the plots for a positive activation with .406 mm (.016 inch) Nitinol, in which a figure-of-eight ligature tie was used to secure the wire in the brackets of all three teeth. Plots for the identical activation with .406 x .559 mm (.016 x .022 inch) stainless steel are shown in figures 28 & 29. The similarity for all plots, both in character and magnitude for such dissimilar wires is quite striking. Analysis of the plots indicates that both wire types are providing virtually no anchorage. The plots for negative activations employing a figure-of-eight tie (Fig. 30 to 33) again show a pattern of similarity between the two wires. However, in this case, activations exceeding 4 degrees overloaded the machine (accounting for the abbreviated plots) indicating substantial support against movement. Analysis of the effects of activation on the ligature, explain the above results.

Examination of figures 27 and 31 demonstrates how the figure-of-eight tie clearly produces a positive z force in the unactivated condition. The result is essentially a force on the F.I.L. tooth in the manner of a positive activation. With the actual positive activation, as performed on the apparatus (Fig. 26 - 29) the F.I.L. tooth and ADJACENT teeth move in a manner which results in a decrease in interbracket distance. The ligature is non elastic and hence does not adapt. Therefore, positive activation loosens the ligature, resulting in the wire no longer being held tightly in the bracket slot. This loosening occurs regardless of the type of wire in the slot, and eliminates the support the FIRST IN LINE tooth receives from the ADJACENT teeth. Deactivation (Fig. 27) results in reestablishing the Pz force present in the initial unactivated state.

With reverse activation, the teeth continue to rotate away from each other, progressively increasing the interbracket distance. The result is tensile loading of the ligature, which after a small degree of rotation (approximately 4 degrees) appears to hold the teeth together preventing any further rotation. As the data shows, this 'restraining' effect of the ligature is also independant of wire type.

Therefore, though 'figure-eighting' can substantially increase anchorage capacity, the initial tension produced when tying the figure-of-eight introduces a force which may undermine its effectiveness. When employing a figure-of-eight the ligature should be so positioned such that any reactive moment will place a tensile stress on it. In certain instances, this may only be possible by tying to buttons on the lingual surfaces of the teeth.

For example, it is common practice when retracting cuspids to 'figure eight' the molars and bicuspids by means of the buccal brackets. However, when viewed from the buccal, the reactive moment on the molar that results from the retraction, will cause a decrease in interbracket distance between the molar and the adjacent bicuspid (i.e. equivalent to a positive activation in our study). Therefore, in this instance, tying on the buccal provides no added anchorage capacity. However, the use of lingual buttons on the molar and bicuspid(s), will allow a figure-of-eight tie which produces the correct stress on the ligature, as molar rotation associated with cuspid retraction increases intertooth distance on the lingual aspect. Therefore, decisions regarding banding and bonding sequence should include analysis of how lingual attachments may be used to improve anchorage in critical areas.

5.8 SUMMARY

An investigation of the anchorage capacity of low modulus archwires was undertaken. The results of this study indicate that significant movement of the first in line anchor tooth will occur when these wires are used for initial alignment procedures. The lack in rigidity of the wire is not compensated for by having multiple teeth in the anchor unit. The variabilty of such factors as interbracket distance, ligation technique, and slot size are considerations which require further investigation. The present apparatus could accommodate such modifications, and thereby provide further insight and information.

The stability of anchor segments secured with rectangular wire was also examined. The assumption that these wires produce absolutely rigid anchorage segments was brought into question. Forceful contact between the edge of a rectangular wire and the ligature was shown to cause permanent deformation of the ligature. This may lead to rotation of teeth, as the wire is no longer fully engaged within the bracket slot.

Finally, the effect of employing a figure-of-eight tie in the anchor segment was studied. The data demonstrated that stressing the ligature in tension produces substantial anchorage capacity regardless of the size of wire within the bracket slot. This tensile loading of the ligature occurs when tying the segment on the side where reciprocal forces and moments will cause the teeth to rotate away from each other. The use of lingual attachments where necessary to ensure tensile loading of the figure-of-eight is recommended as an effective means of augmenting anchorage. Conversely, using a figure-of-eight where reciprocal forces and moments on the anchor unit cause a decrease in interbracket distance, causes the ligature to loosen, and results in essentially a zero increase in anchorage. This effect is also independent of wire size. However, the initial tension produced when securing the figure-of-eight tie, introduces a force which tends to decrease the tension on the ligature, so necessary for it to be effective.

Chapter VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The purpose of this investigation was to determine the intramaxillary anchorage capacity of selected low modulus and rectangular archwires. A modified version of the apparatus employed by Levin (1985) was used. Analysis of the data obtained led to the following conclusions:

1. The modified apparatus proved suitable for determining the three-dimensional forces and moments which support the first in line tooth of a three tooth anchor segment.
2. When using flexible wires for initial alignment, significant rotation and tipping of a tooth next to a malaligned tooth will occur.
3. Frictional forces will prevent mesial-distal 'jiggling' of the first in line anchor tooth, when it is coupled to a buccally displaced tooth. When coupled to a tooth in lingual version, friction is greatly reduced and 'jiggling' likely occurs.
4. Rotational anchorage with rectangular wire is not as rigid as expected. Deformation of the ligature will occur when the rectangular wire makes forceful contact with it. The likely result is lack of complete wire engagement, leading to differences in second and third order orientation between neighboring teeth.

5. Ligature deformation appears to be due to, the rectangular wire exceeding the bending stiffness of the ligature , as well as the sharp edge of the wire 'gouging' the ligature surface. As such, employing a larger ligature helped decrease deformation by 60%.
6. Tying the ligature on the side of the bracket where the wire will contact it, does not improve the ligature's resistance to deformation, despite the fact that the ligature contains more wire on the tied side.
7. When using a figure-of-eight ligature tie to connect teeth in the anchor segment, the archwire contributes nothing to the anchorage capacity.
8. Placing a figure-of-eight tie on the side of the anchor segment where teeth tend to rotate toward each other causes the ligature to loosen. The result is essentially a zero increase in anchorage, regardless of the wire connecting the teeth.
9. Tying the figure-of-eight such that movement within the anchor segment places a tensile stress on the ligature results in a substantial increase in anchorage capacity, regardless of the wire in the brackets.
10. Analysis of the expected reactive movement within an anchor segment will in some instances require that lingual attachments be placed in order to ensure placing the correct stress on the figure-of-eight tie.
11. Unfortunately, the initial tension produced when securing the figure-of-eight tie produces a force which would tend to loosen the ligature, thereby potentially decreasing its effectiveness to augment anchorage.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the results of the present study, recommendations for future research include:

1. an investigation employing varying interbracket distances within the anchor segment.
2. an examination of anchorage capacity in different directions, (i.e.), rotation about the mesial-distal axis.
3. a study of anchorage comparing .457 x .635 mm (.018 x .025 inch) brackets with .559 x .711 mm (.022 x .028 inch) brackets.
4. an examination employing brackets which do not require ligatures.
5. an examination of the anchorage capacity of low modulus rectangular wires.

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Appendix A

GRAPHS DEPICTING FORCE & MOMENT LEVELS VS. ROTATIONAL ACTIVATION (AY)

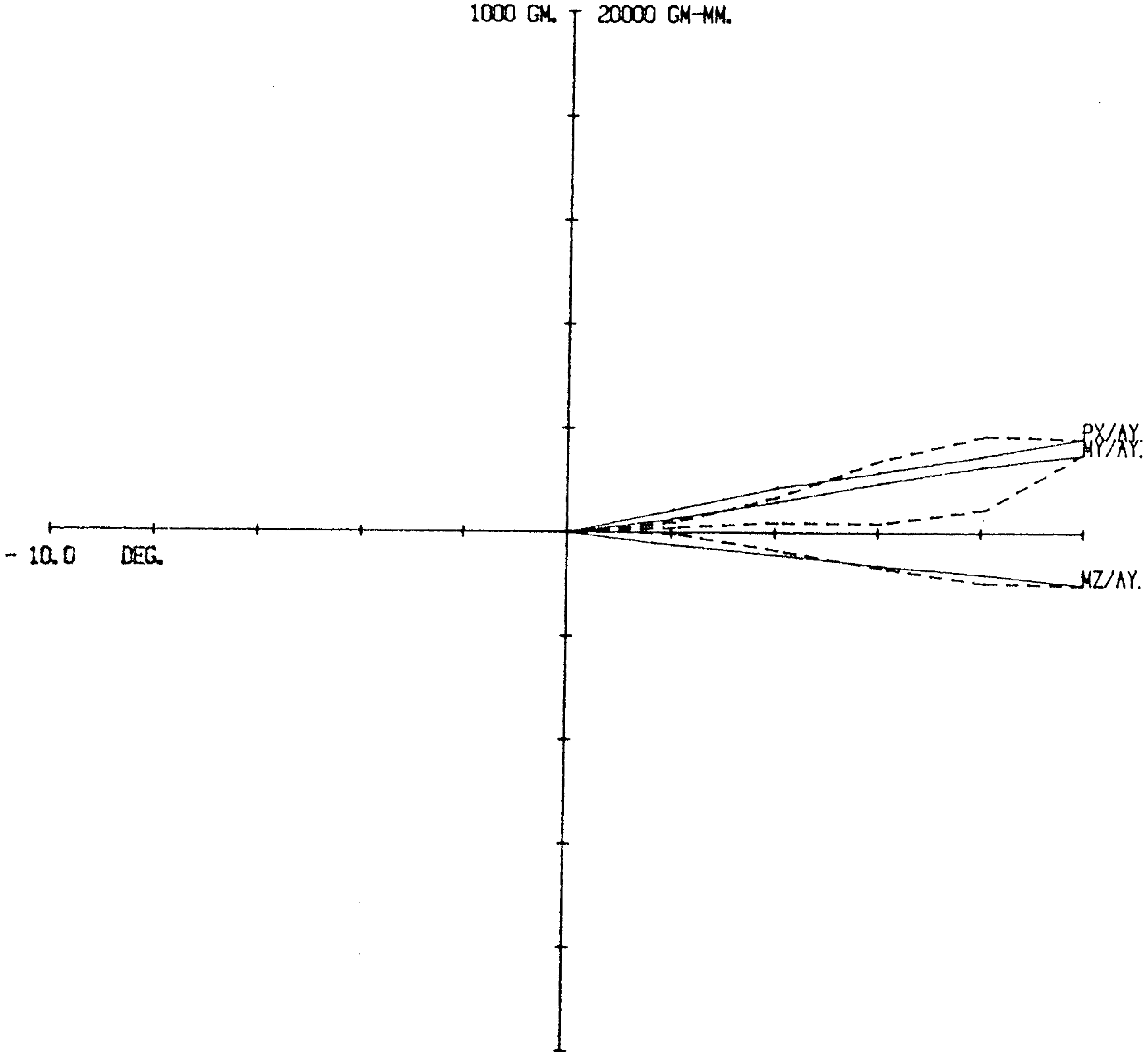

Figure A.1: .406 mm (.016 inch) T.M.A. - positive activation

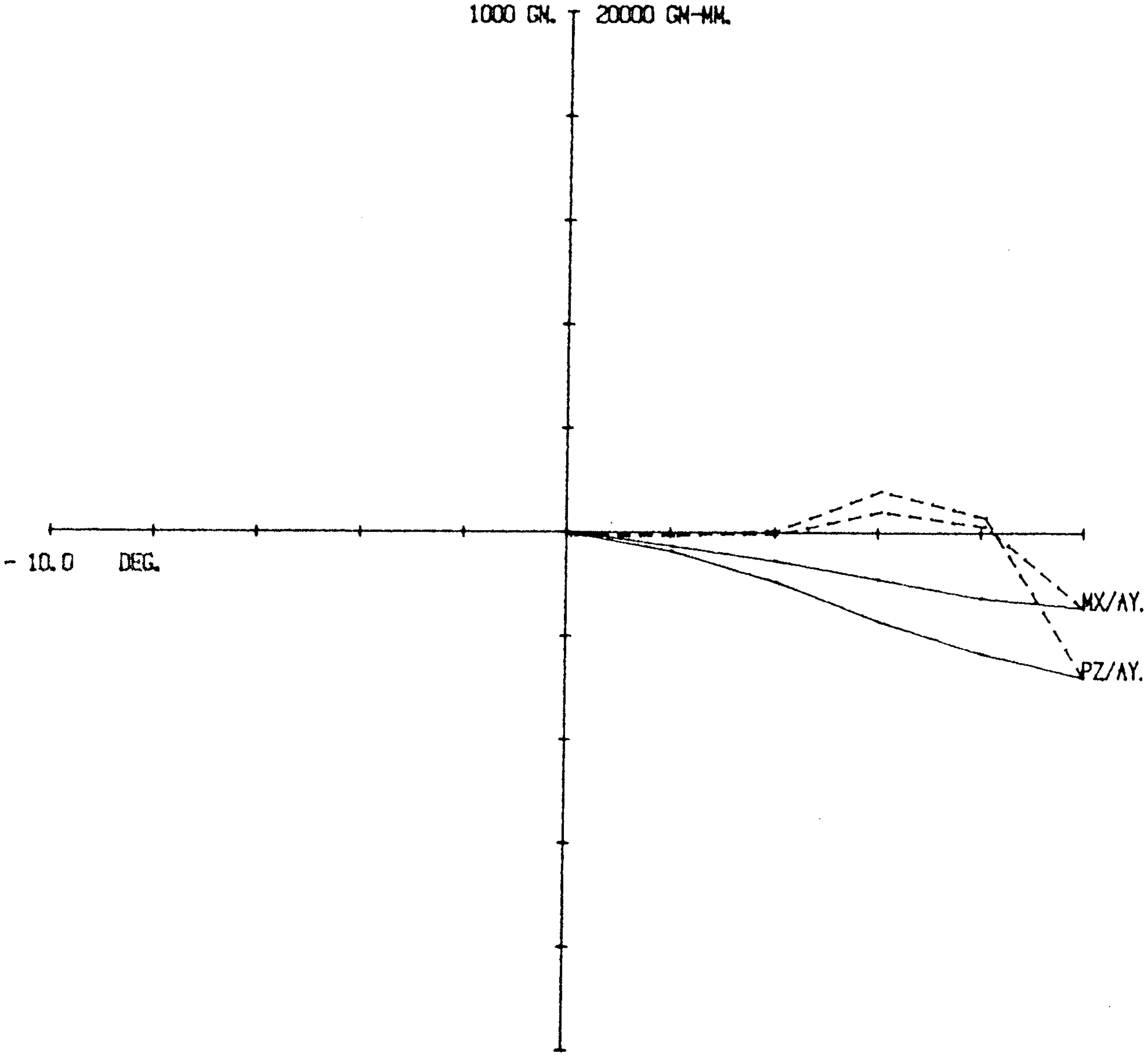

Figure A.2: .406 mm (.016 inch) T.M.A. - positive activation

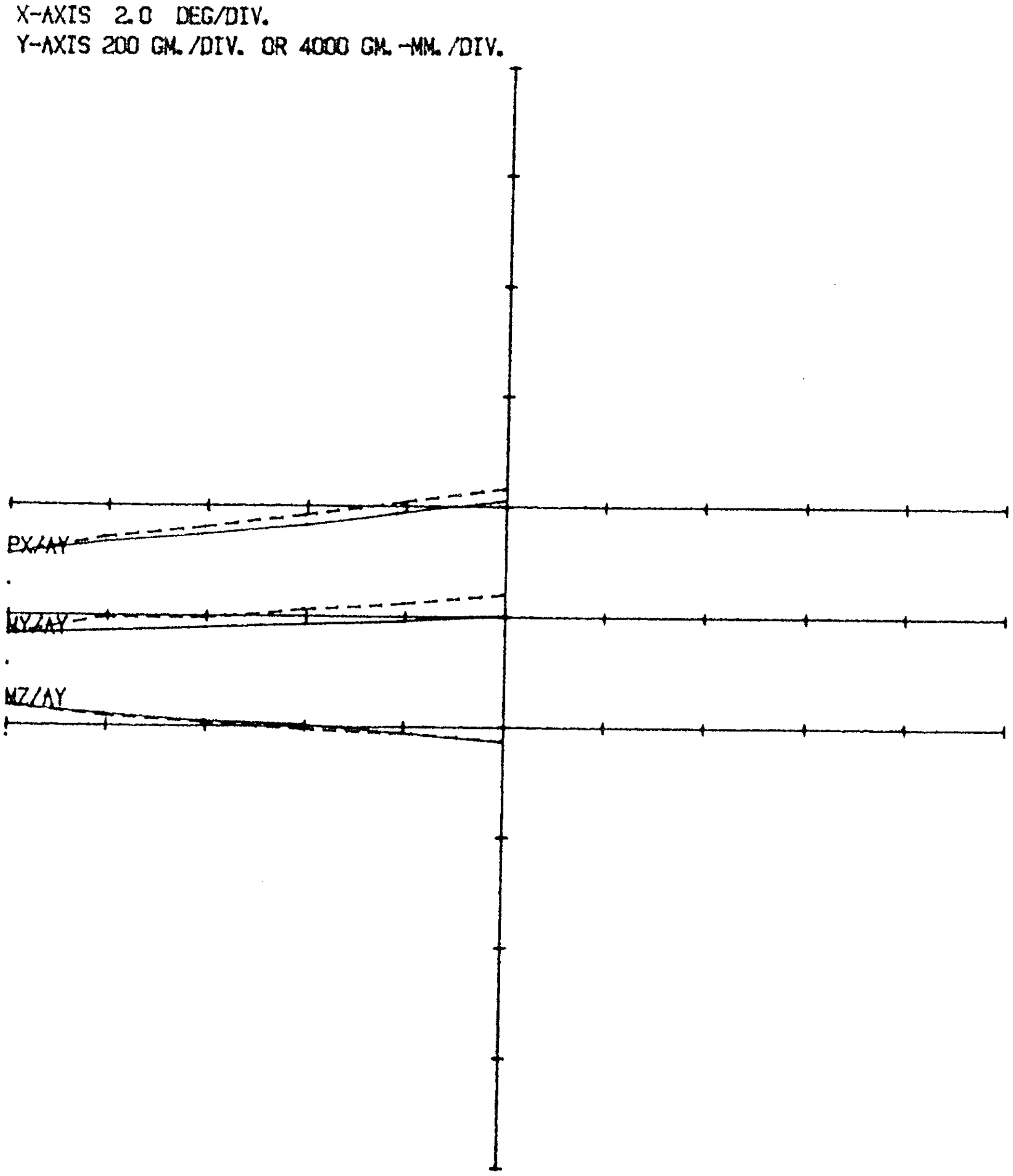

Figure A.3: .406 mm (.016 inch) T.M.A. - negative activation

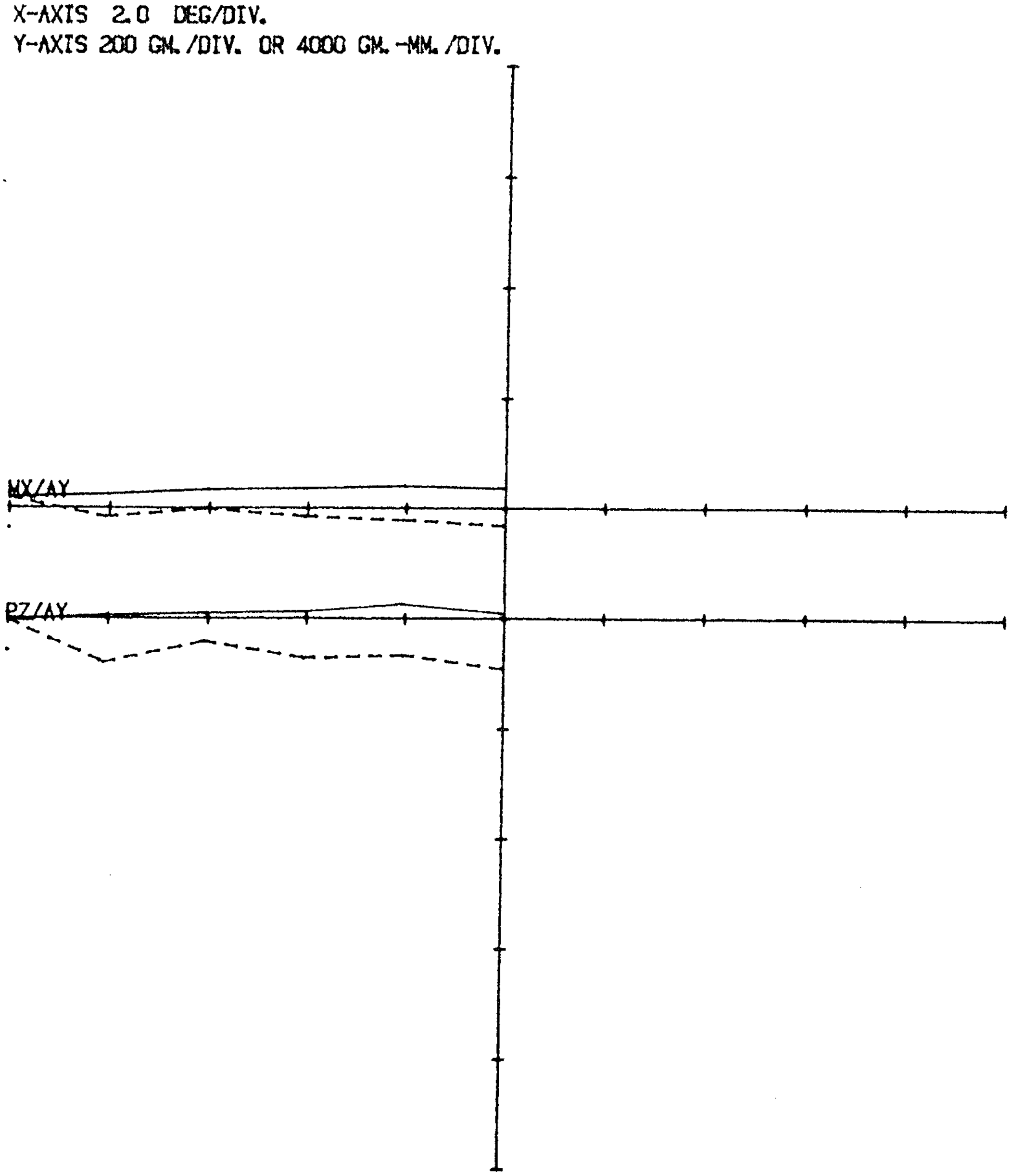

Figure A.4: .406 mm (.016 inch) T.M.A. - negative activation

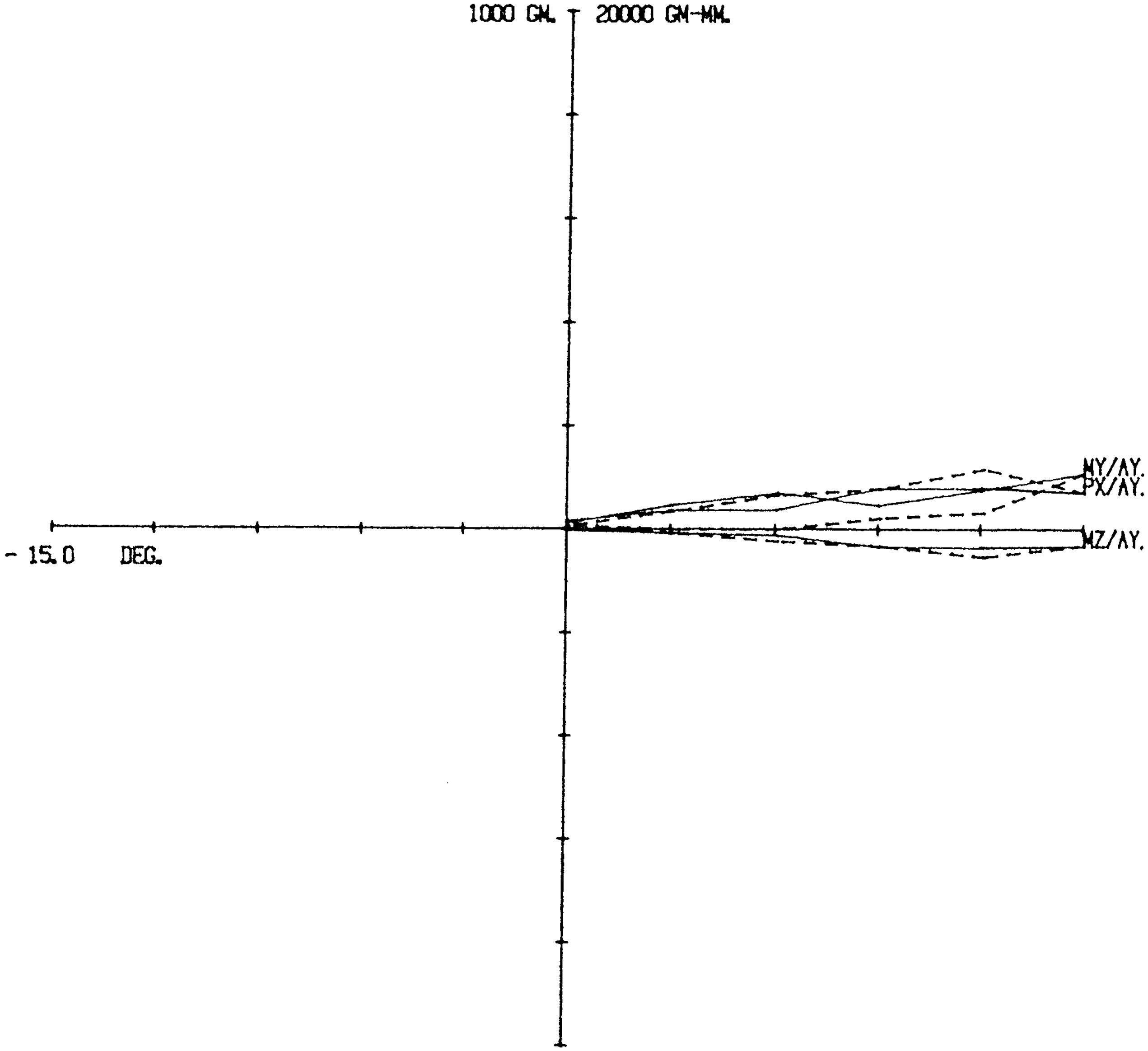

Figure A.5: .381 mm (.015 inch) Twistflex - positive activation

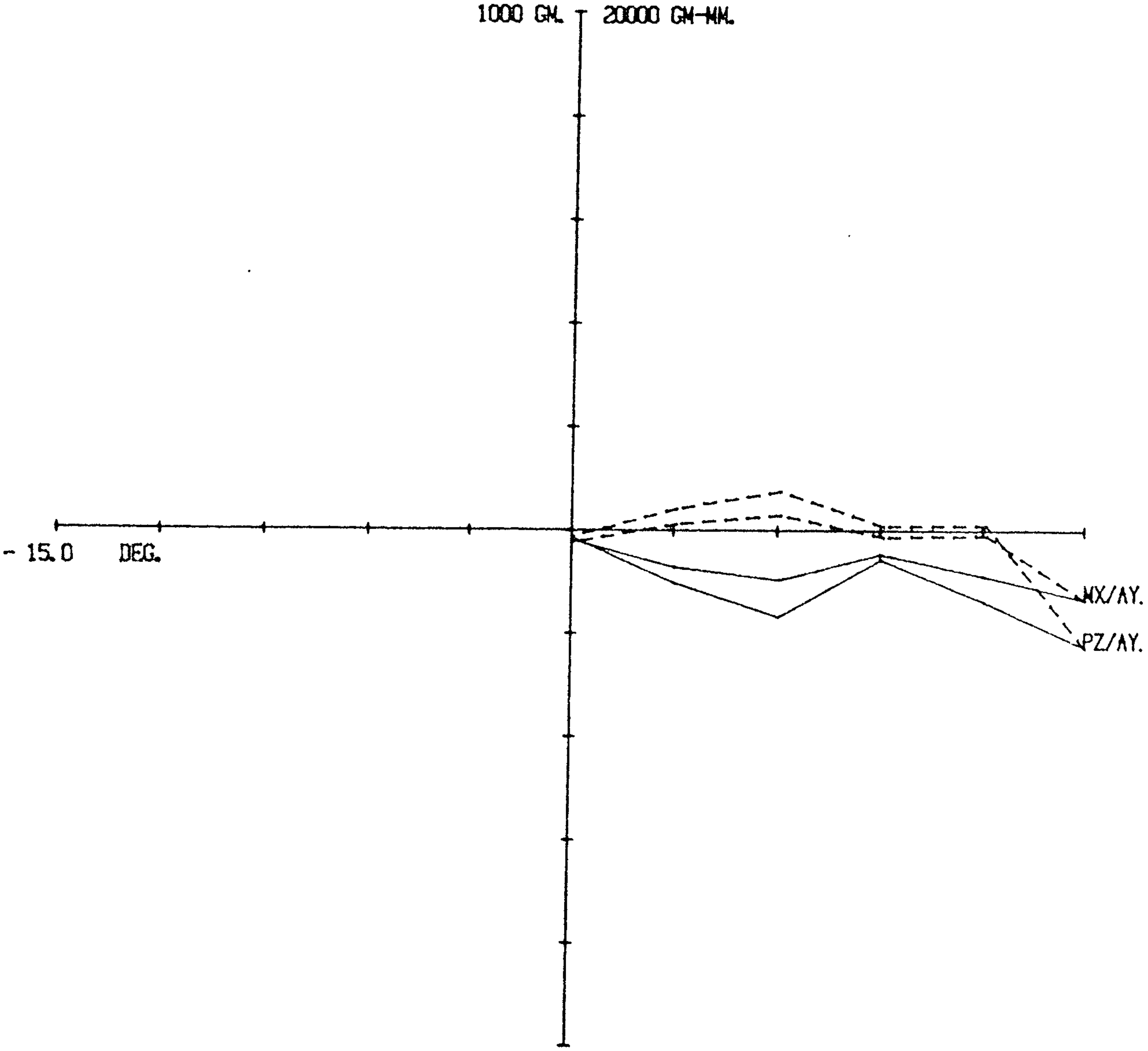

Figure A.6: .381 mm (.015 inch) Twistflex - positive activation

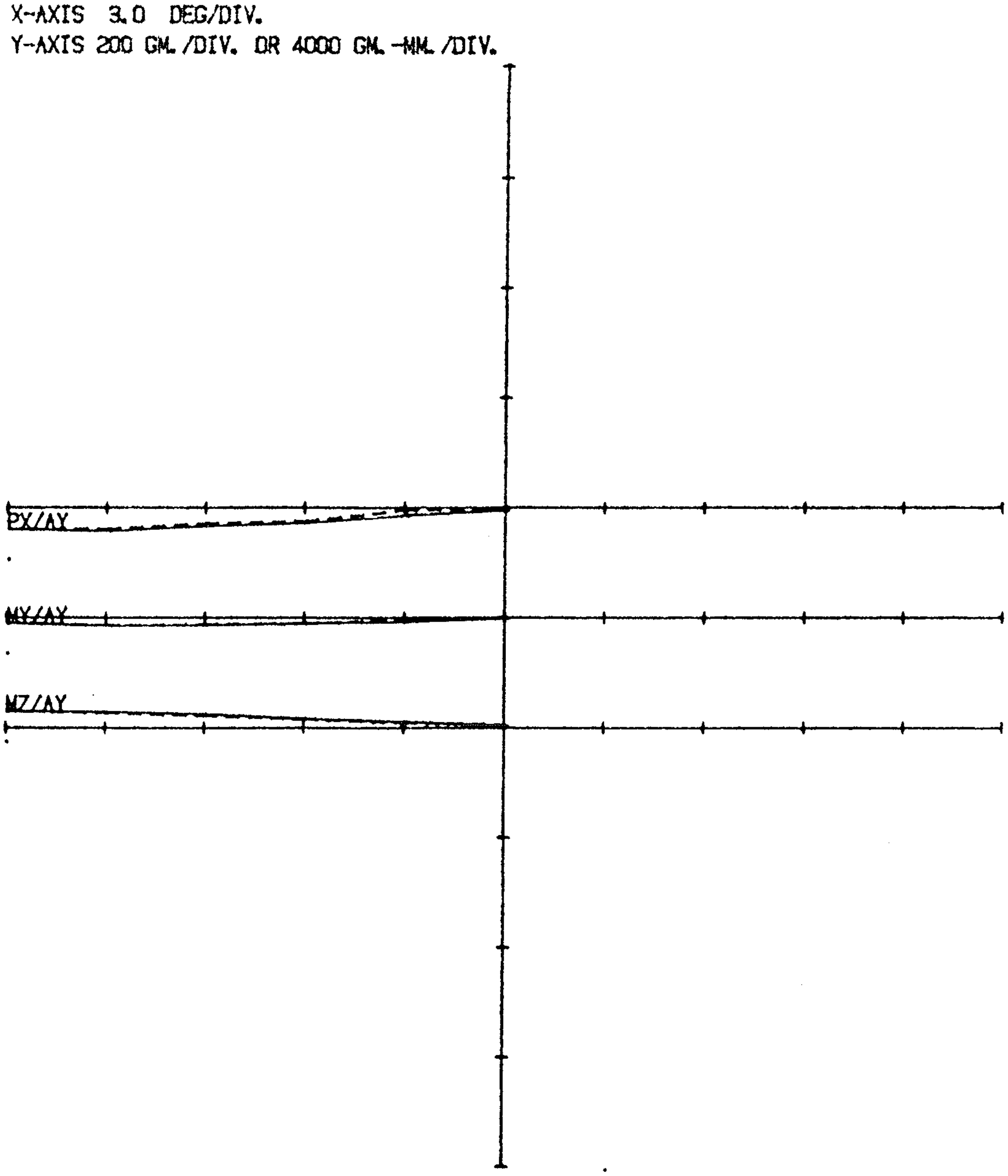

Figure A.7: .381 mm (.015 inch) Twistflex - negative activation

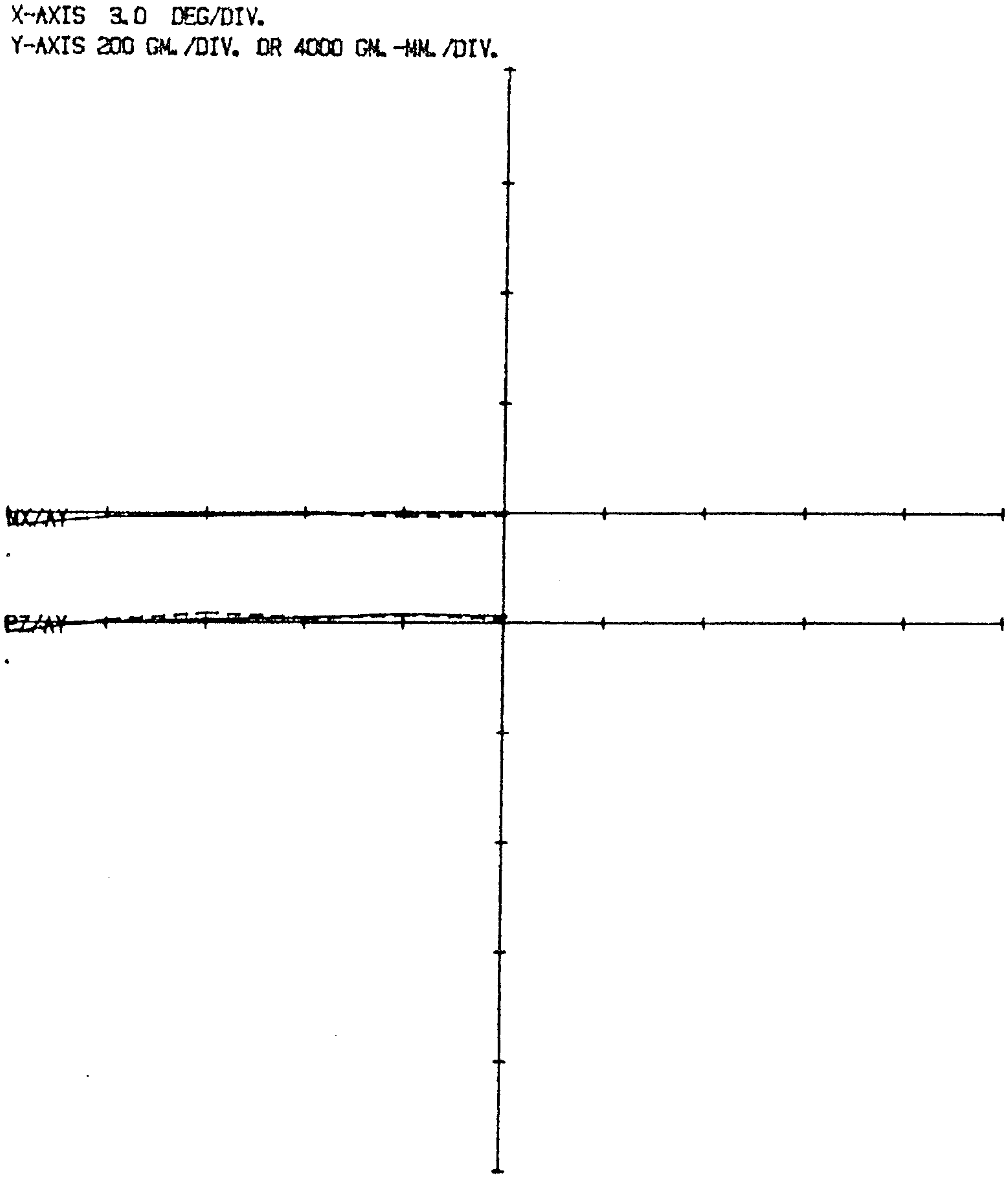

Figure A.8: .381 mm (.015 inch) Twistflex - negative activation

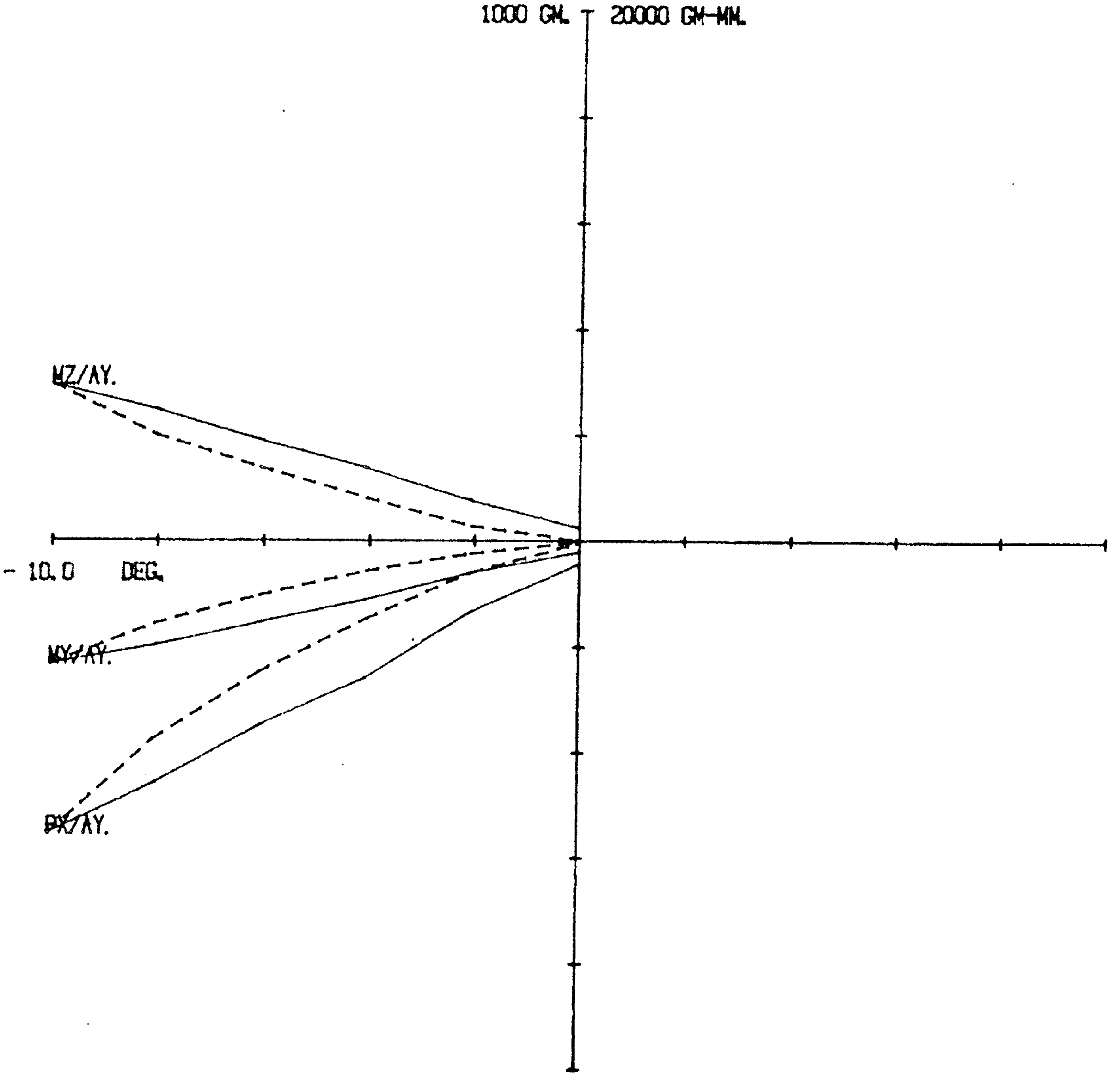

Figure A.9: .406 x .559 mm (.016 x .022 inch) stainless steel - negative activation, reverse ligature tie #1

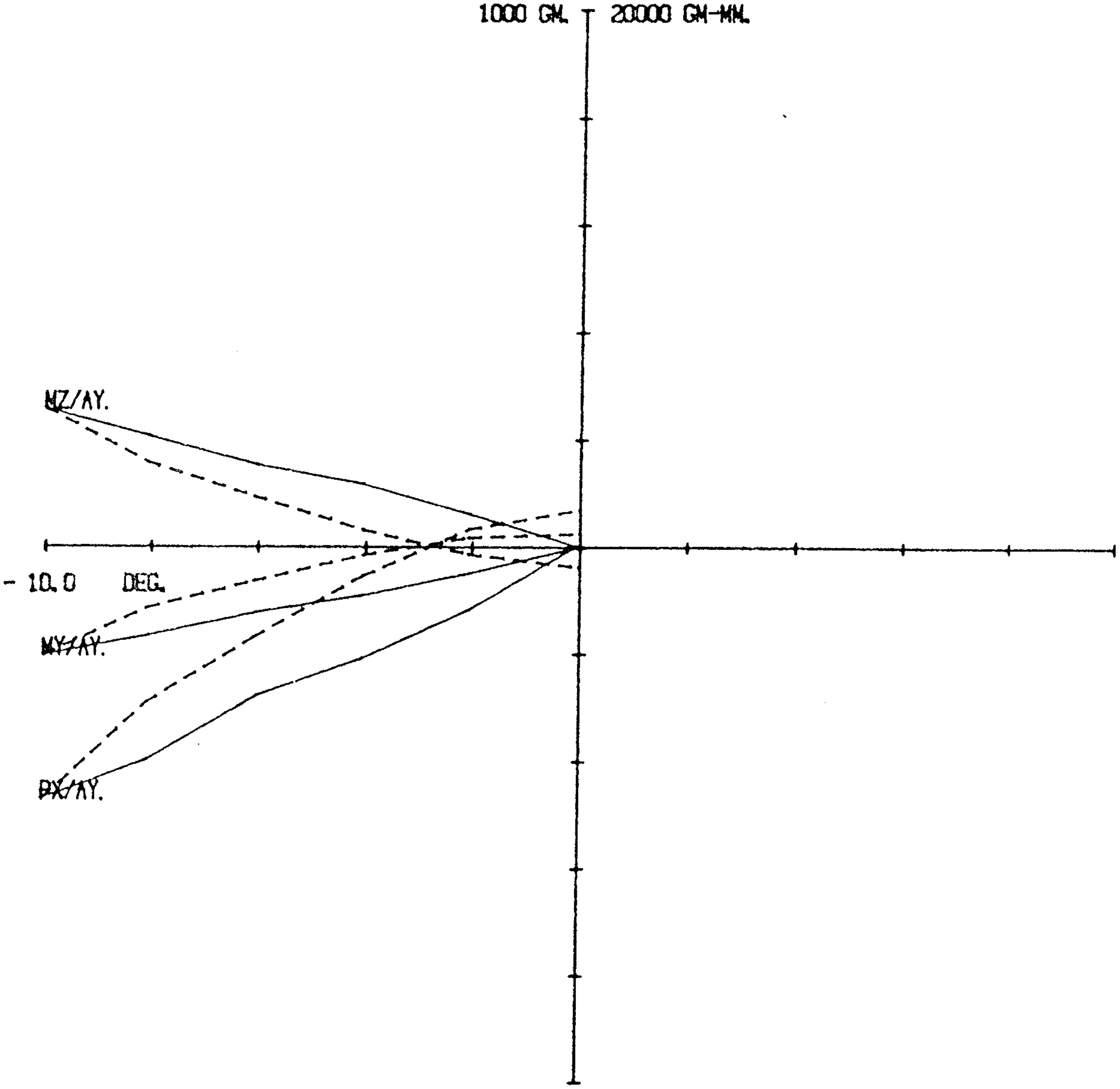

Figure A.10: .406 x .559 mm (.016 x .559 inch) stainless steel - negative activation, reverse ligature tie #2

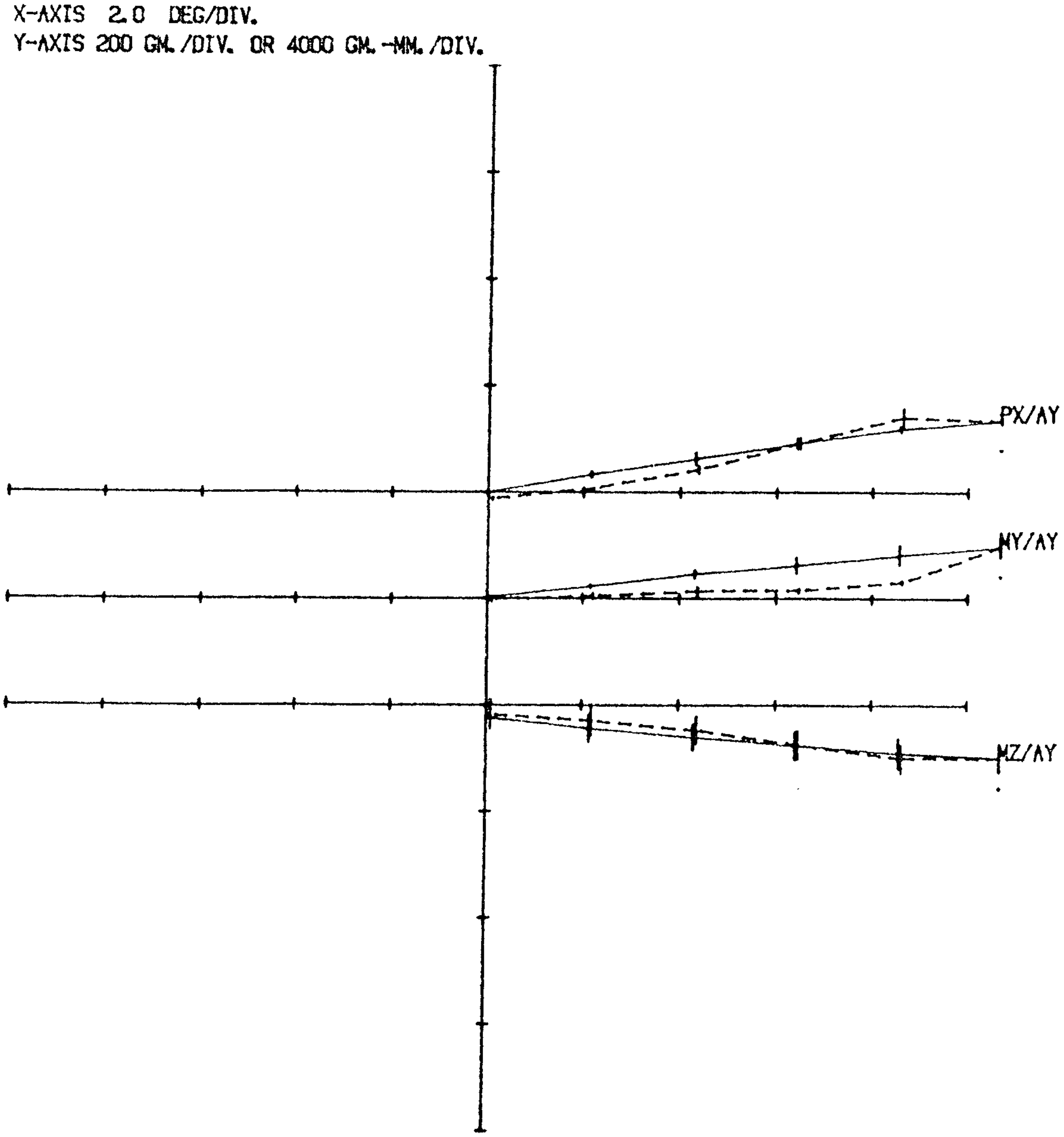

Figure A.11: .406 mm (.016 inch) Nitinol - averaged plots for positive activation

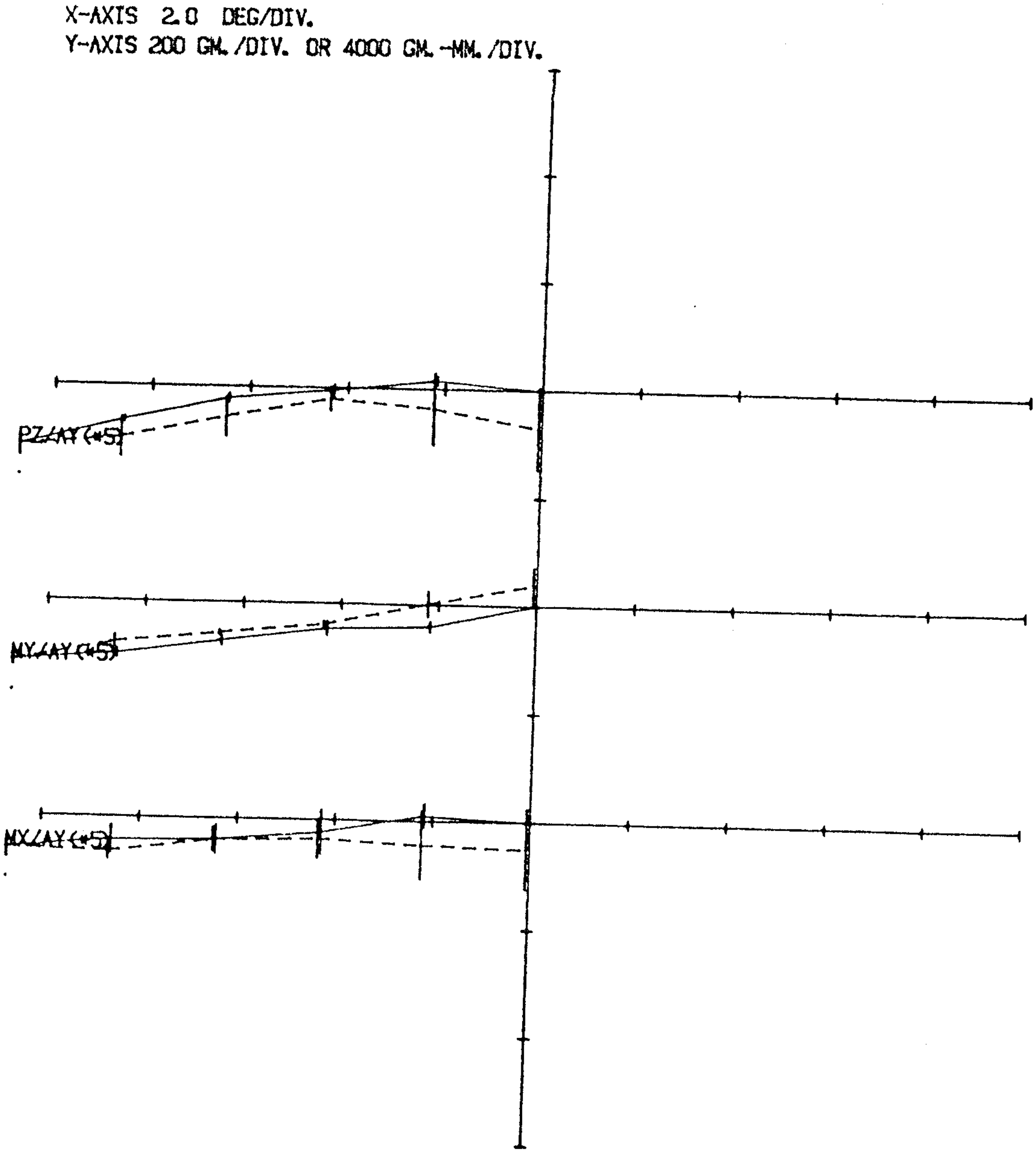

Figure A.12: .406 mm (.016 inch) Nitinol - averaged plots for negative activation with zero shift and multiplication

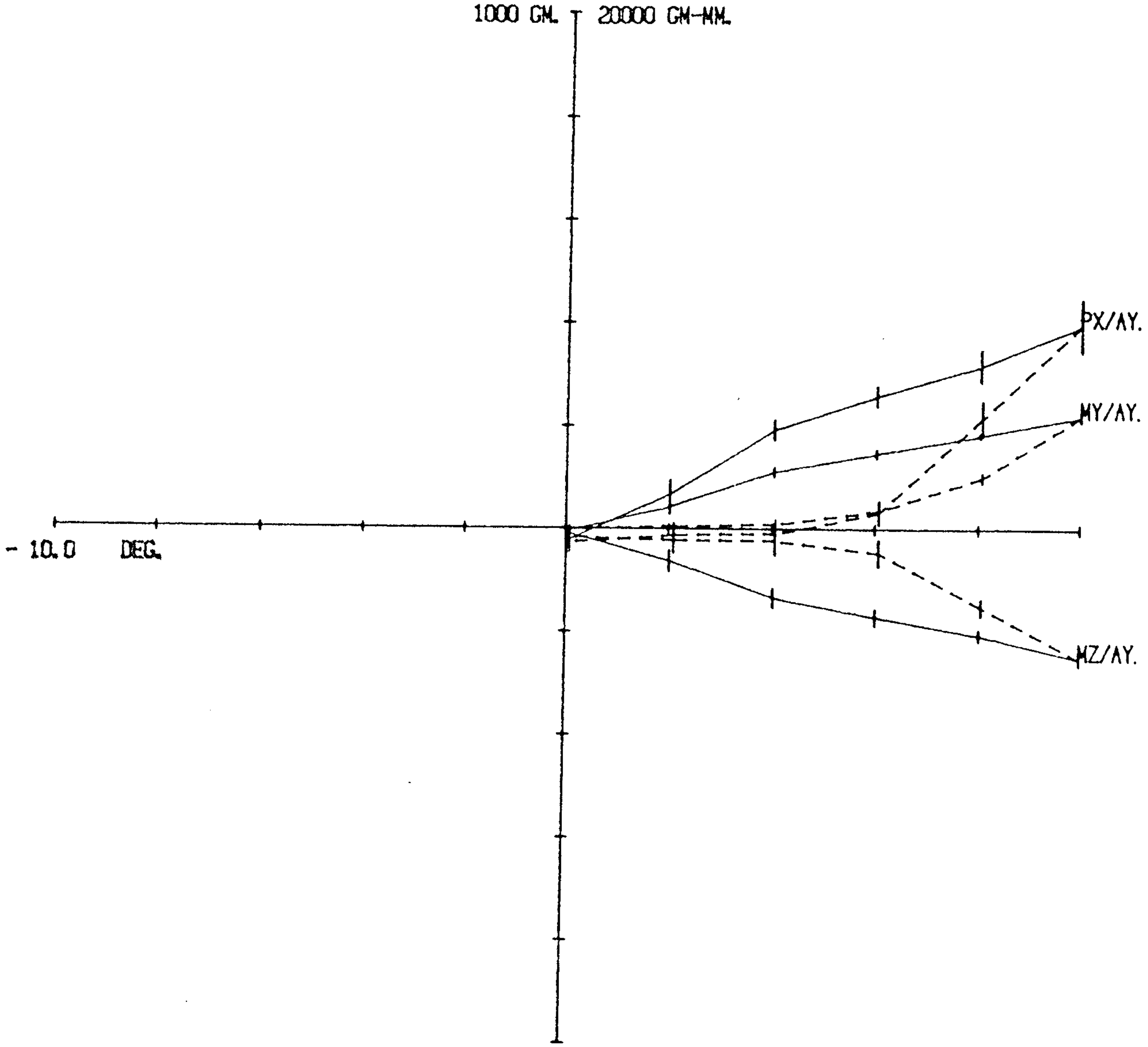

Figure A.13: .406 x .559 mm (.016 x .022 inch) stainless steel - averaged plots for positive activation

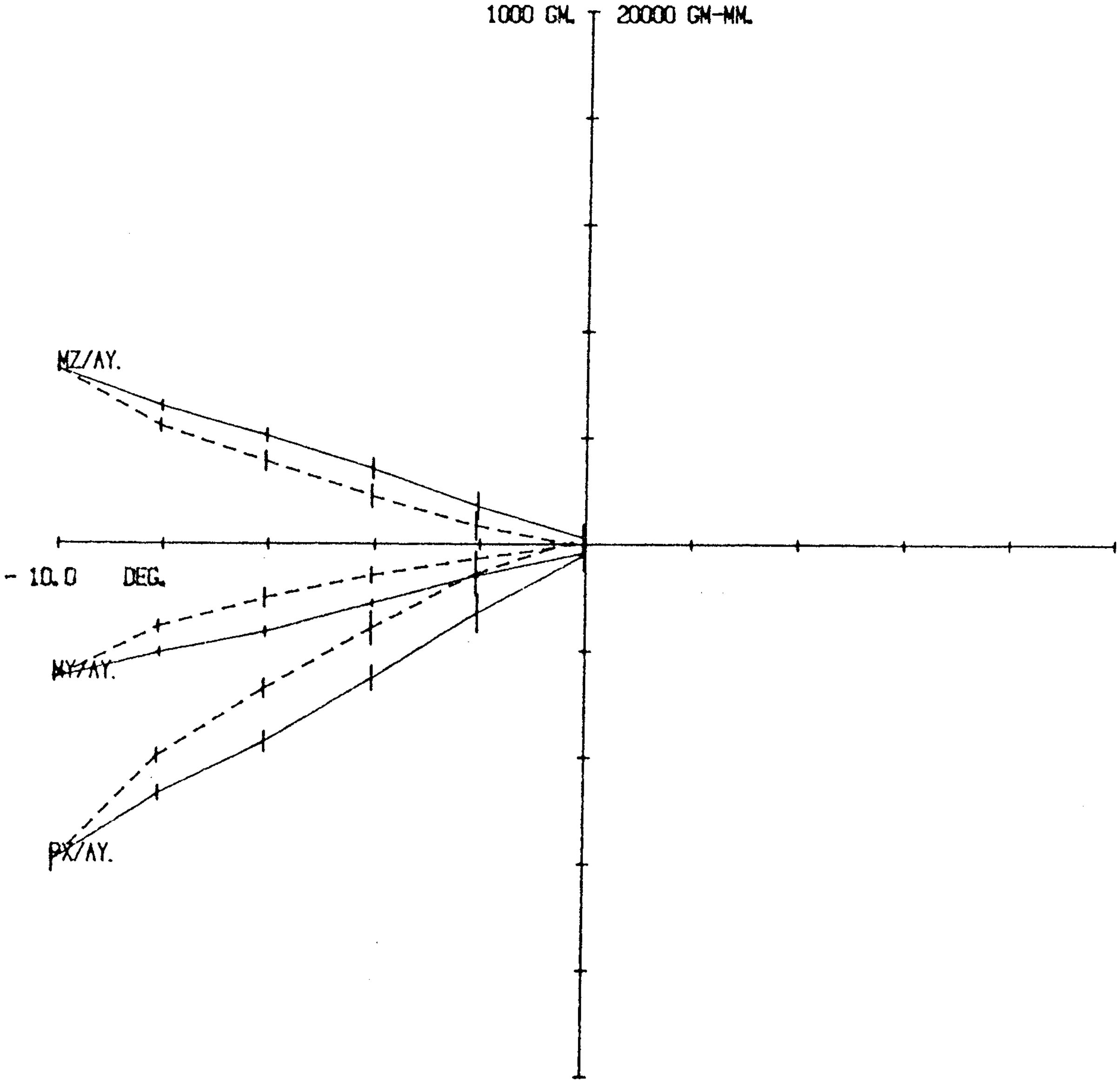

Figure A.14: .406 x .559 mm (.016 x .022 inch) stainless steel - averaged plots for negative activation

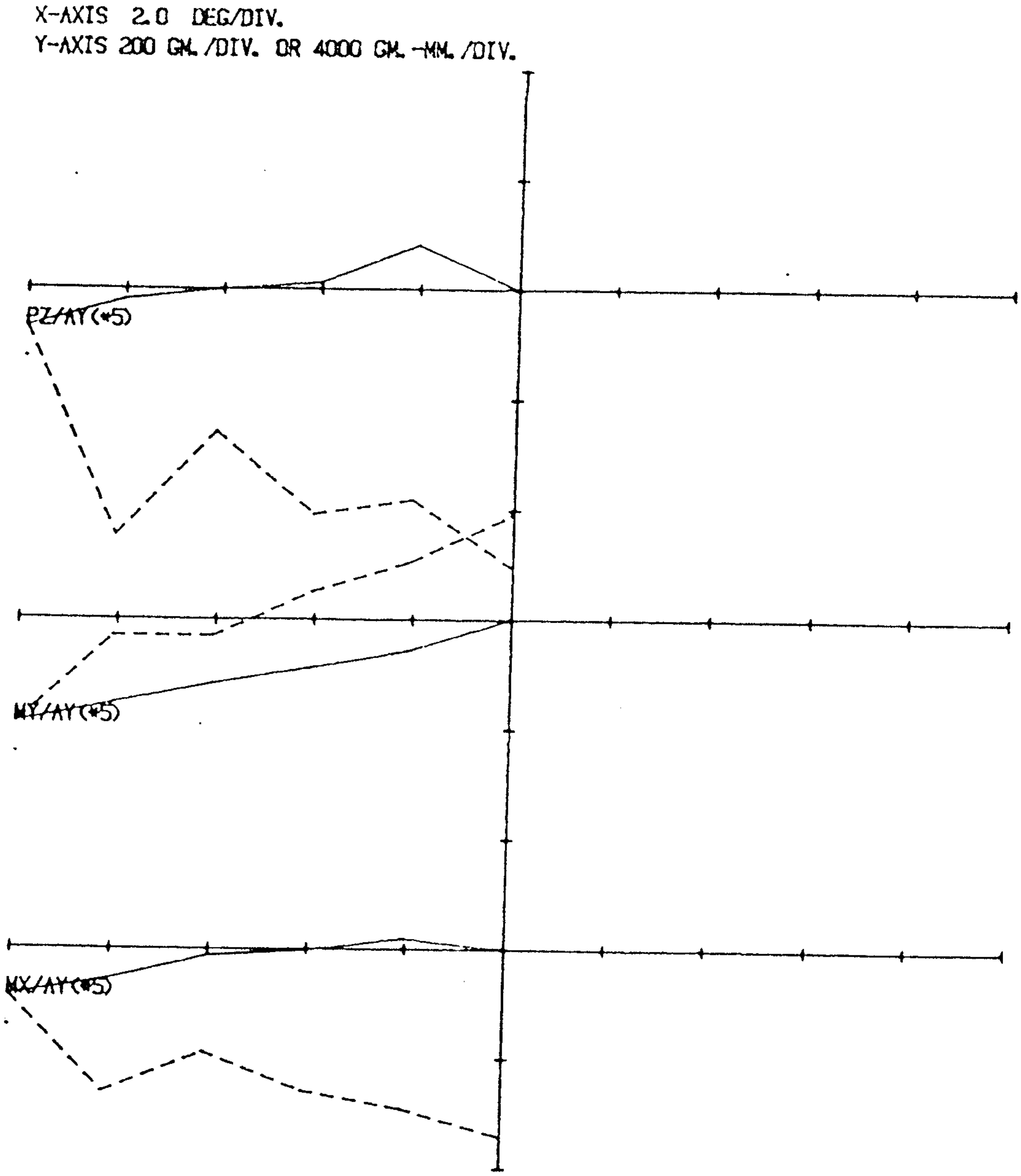

Figure A.15: .406 mm (.016 inch) T.M.A. - negative activation with zero shift and multiplication

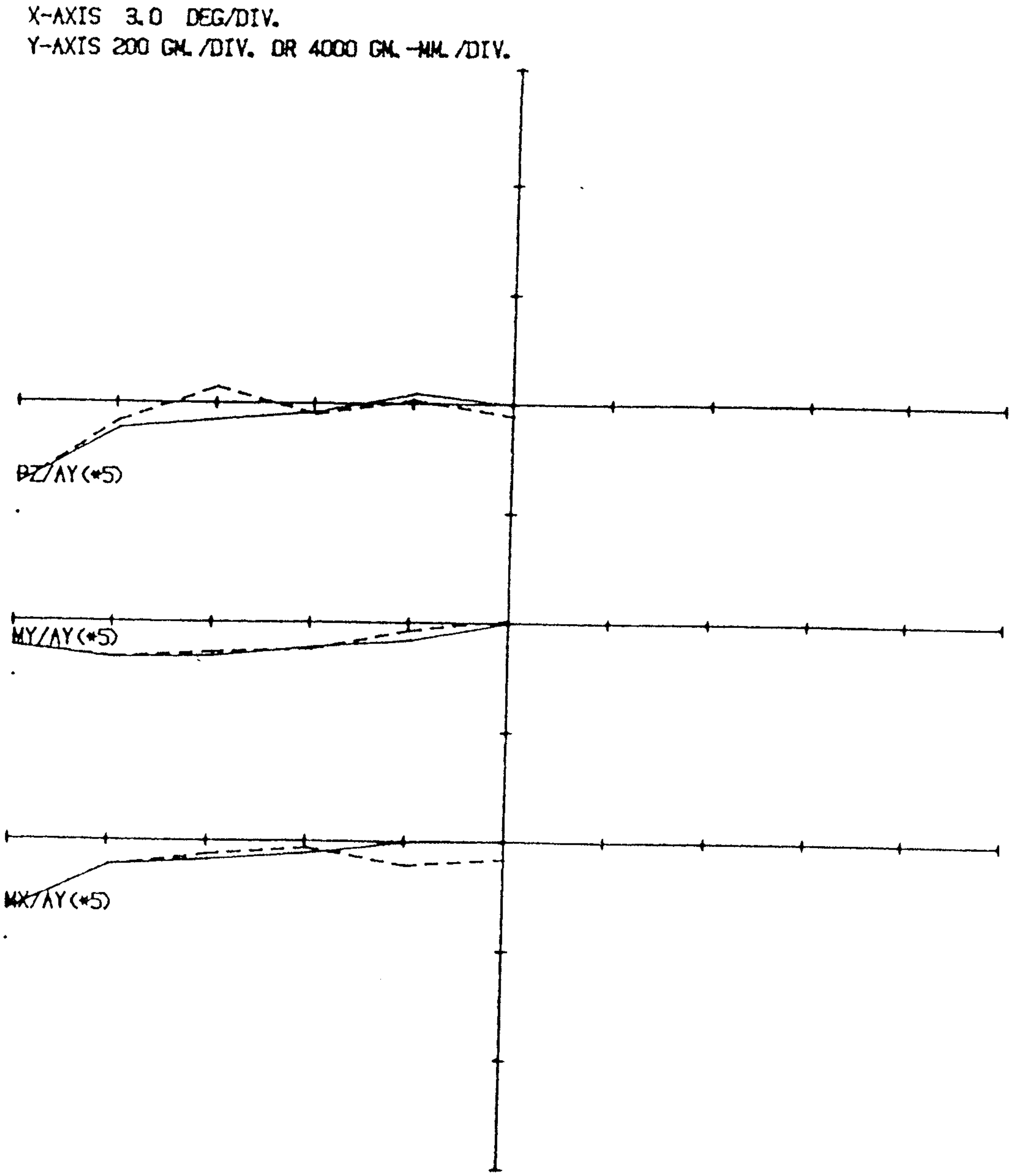

Figure A.16: .381 mm (.015 inch) Twistflex - negative activation with zero shift and multiplication