THE RATE OF TOOTH MOVEMENT
IN RESPONSE TO
KNOWN APPLIED FORCE SYSTEMS

by

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A thesis submitted to the Faculty of Graduate Studies of
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ABSTRACT

The orthodontic literature contains numerous conflicting accounts regarding the ideal or optimal force requried for orthodontic tooth movement. Lack of agreement amongst the various authors can partially be explained by the difficulty encountered in obtaining adequate quantitative data. This study utilized both in vivo and in vitro techniques developed by Duff (1987) and Sonya (1987) to obtain adequate quantitative data of tooth movement and applied force systems in three dimensions. By examining the rate of tooth movement in response to known applied force systems it was hoped that a better understanding of the concept of optimal force could be obtained.

In vitro measurements of the force systems of appliances used to retract cuspids in vivo was done on a machine developed at the University of Manitoba. A passive wire template fabricated in vivo facilitated the orientation of the appliances in vitro. In conjunction with the calibration of the force system, a technique was adopted using study casts to accurately measure the three dimensional changes in tooth position as a direct result of applied orthodontic force.

Analysis of the limited data obtained in this manner indicates:

1. There is likely not one optimal force level for any particular type of tooth movement. Instead, there is

evidence to suggest that the optimal force level differs for each phase of tooth movement.

2. Tooth movement in any one direction does not occur in a straight path but instead follows a jiggling process.

3. Tooth movement occurs in the directions that may be anticipated from an analysis of the force system applied without any clinically unacceptable movement.

4. The stiffness of the appliance in the directions in which tooth movement is not wanted inhibits unwanted tooth movement.

5. Establishing stable anchor segments which could be used to monitor tooth movement of the cuspid is possible. Likewise, a chosen point on the palatal rugae can act as a stable reference over short periods of time.

DEDICATION

This thesis is dedicated to
my parents, Lewis and Sonia Cohen
without whom my education
would have been impossible.

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1. INTRODUCTION

The term "optimal force" has constantly surfaced in the orthodontic literature over the past few decades. Traditionally optimal force has been defined as the ideal force necessary to produce the greatest amount of tooth movement in the shortest time with minimal amounts of tissue damage, patient discomfort, and unwanted tooth movement. At present there is no refined means of directly assessing tissue damage in response to tooth movement in humans. On the other hand, the technology does exist to enable the other components that define optimal force to be studied at least in greater detail.

The orthodontic literature contains numerous conflicting accounts of the forces required for orthodontic tooth movement. Weinstein and Haack (1959) found that muscular forces with values as low as 1.68 grams were capable of moving teeth. Values as high as 1,515 grams have also been reported (Hixon et al, 1969). Such a wide range of values is in sharp contrast to the precision attempted in cephalometric and other diagnostic techniques in orthodontic treatment.

The large range of required forces suggested in the literature can partially be explained by the difficulty in obtaining adequate quantitative data. Part of the problem results from the fact that techniques that have been available for <u>in vivo</u> tooth measurements or force calibration in three dimensions were unsatisfactory. In many of the experiments the data that has been collected, whether in vivo or in vitro, has been in only two-dimensions.

In order to begin to determine if an optimal force exists, the rate or velocity of tooth movement in response to a given force must be known ie. will a tooth move faster when a heavier or a lighter force is applied? To know the answer to this question, one must be able to determine what force is present at any given time as a tooth moves in response to an applied force. In this study the techniques developed by Duff (1987) and Sonya (1987) have been modified to determine the rate of tooth movement in response to a known force system. In other words, the examination of the inter-relationship between time and tooth movement will be correlated with the changes in the force system as the tooth moves. It is fully recognized that assessment of tooth damage plays an essential part in defining an optimal orthodontic force system. However, time and other limitations did not permit such an assessment in this study.

2. LITERATURE REVIEW

2.1 INTRODUCTION

A controversy over the relationship between the force magnitude delivered by orthodontic appliances and the rate of orthodontic tooth movement has existed for years. The experiments which have shaped this debate all appear to have drawbacks in their experimental design.

Until recently, quantification of data regarding force systems and the resultant tooth movement has proven to be a difficult task. As a result, the question of an optimal force level for orthodontic tooth movement has remained unanswered. The orthodontic literature represents a broad range of acceptable magnitudes of forces necessary to produce particular tooth movements. Values as low as 1.68 grams (Weinstein and Haack, 1959) to as high as 1,515 grams (Hixon et al, 1969) have been reported as being effective and acceptable. In addition, some investigators believe that the duration of the force rather than the magnitude is more important to the biological events associated with tooth movement. (Steenvoorden, 1990).

The diversity of opinion presented in the literature can partially be explained by the difficulty in obtaining adequate quantitative data. For example, there have been no techniques presented for accurately measuring *in vivo* tooth movement. As a result of this difficulty, many of the studies have analyzed a three dimensional problem in two dimensions only. Essentially what is necessary to accurately begin to examine the existence of an optimal force is:

1) a means of analyzing tooth movement in all three dimensions;

2) a means of simultaneously measuring forces and moments in all three dimensions; and

3) knowing how the applied force system changes as a tooth moves.

The purpose of this review is to look at the studies relating tooth movement and force systems and demonstrate some of the problems associated with the collection and interpretation of the data. Particular emphasis will be focused on cuspid retraction primarily because most of the studies in this area have used cupsid retraction as their model.

2.2 CUSPID RETRACTION TECHNIQUES

Cuspid retraction is a common tooth movement in many orthodontic treatment plans. Ideally, from a biological point of view, bodily movement or translation of the cuspid is the desired movement since this provides the most even distribution of stress on the periodontal membrane (Hixon et al, 1970). Bodily movement is most readily achieved when a force is applied through the center of resistance of a tooth (Burstone, 1985). Limitations in orthodontics make this application impossible and orthodontists are thereby restricted to applying forces to a bracket bonded on the crown of the tooth. Only by precisely calculating and implementing a counter moment at the bracket to compensate for the moment produced at the center of resistance can translation be achieved (Burstone, 1985). Applying a counter-moment at the bracket precisely equal to that produced at the center of resistance is a difficult task. As a result, with the application of a force at the bracket in the distal direction, the expectation of some distal tipping and disto-lingual rotation of the crown is a realistic one (Nikolai, 1975). In fact, it has been hypothesized that most retracting devices used in orthodontics produce a series of tipping and uprighting movements (Hixon and Klein, 1972).

Attempting to translate cuspids during retraction has been the focus of many inventive cuspid retraction devices (Lack, 1980). The progression in the development of these devices was initially empirical in nature. Only after the development of instruments capable of measuring both forces and moments (Burstone, 1962; Paquien, 1978) has the development of cuspid retraction devices been based on more sound mechanical principles.

Farrant (1976) reviewed several cuspid retraction devices including coil springs, elastics and loops. Farrant identified two categories of appliances - those that are frictionless and non-frictionless. Friction, or sliding mechanics, often utilizes a continuous arch wire and has the disadvantage of being considered a statically indeterminate system. A statically indeterminate system is defined by the inability to directly measure the forces and moments due to the interaction of the force system developed at the active and reactive units. A necessary prerequisite in the examination of the rate of tooth movement in response to known applied force systems is to be able to determine the force system. Because this determination is virtually impossible to do using sliding mechanics, only the segmental approach as introduced by Burstone (1966) is appropriate for determining the force\velocity relationship of tooth movement. The segmental technique is based on the concept of a "two-tooth" system whereby the anchor segment is rigidly held together by a full-dimension arch wire while the tooth in question (in this case the cuspid) is acted upon by a more flexible, lighter, active wire (Burstone, 1962a, 1982). In this way, the anchor segment represents one tooth while the tooth being activated represents the other tooth. Using this technique the force system now becomes a determinate system (Burstone et al, 1973).

2.3 MEASUREMENT AND EVALUATION OF FORCE SYSTEMS

The desire to quantify the forces generated by orthodontic appliances is not a new one (Fish, 1917). One of the first instruments designed solely for measuring orthodontic forces was built in 1920 by a German orthodontist by the name of Borschke (Paulich, 1939). Many other instruments were designed in the years following this initial design (Irish, 1927; Peyton, 1933; Richmond, 1933; Wirt, 1935; Brumfield, 1937; Paulich, 1939; Storey and Smith, 1952; Burstone, 1961). These devices were reviewed by Lack (1980).

The measurement of orthodontic forces in three dimensions simultaneously was first done by Teasley et al (1963). Although the instrument he used was reported to be accurate to within two percent, it was incapable of measuring the forces exerted on a tooth but rather the "potential" of an appliance.

Burstone et al (1973) employed a technique using strain gauges and transducers that allowed a force system to be analyzed in three-dimensions. Subsequent results using this instrument could not be found in the literature.

Paquien (1978) developed an instrument capable of measuring forces and moments of an appliance in all three dimensions during various positions of appliance activation. Six strain gauge force transducers were used in conjunction with a mini-computer for the acquisition and interpretation of the data. Forces of up to 100 grams were capable of being measured. The measurements of moments were prevented because of difficulties encountered. In 1979, McLachlan modified this measuring device so that it was capable of measuring forces and moments in three dimensions up to 130 grams and 2300 gram-millimeters within a plus or minus 3% accuracy. The machine has since been modified so that it is currently capable of measuring forces and moments in three dimensions up to 1,000 grams and 20,000 gram-millimeters respectively, still within a plus or minus 3% accuracy.

2.4 MEASUREMENT OF TOOTH MOVEMENT

Examination of the rate of tooth movement necessitates that a measurement of tooth movement must take place. Over the years, many investigators have attempted to develop a method to accurately measure tooth movement both in vivo and in vitro.

In vivo tooth movement measurement has been attempted with the aid of calipers, acrylic templates or jigs, and levels (Burstone and Groves, 1960; Andreasen and Johnson, 1967; Huffman and Way, 1983). One of the many difficulties encounterd in in vivo measurements is the accurate position and orientation of the selected reference points . Even if this problem could readily be overcome, these in vivo techniques do not make it possible to accurately measure linear tooth movement in all three dimensions. Rotational tooth movement in all three dimensions presents an even more difficult task.

In vivo tooth measurement in three dimensions was first successfully accomplished using holography (Pryputniewicz et al, 1978; Pryputniewicz and Burstone, 1979). While this technique enables measurements to be accurate to within 0.05 micrometers, it can only do so over time intervals of less than two minutes.

Because accurate in vivo measurement of tooth movement, especially in three dimensions, had proven to be a difficult task, many investigators inevitably turned to in vitro methods of analysis. Attempts at integrating either intraoral photographs (Andreason et al , 1984) or extraoral photographs of dental casts (Biggerstaff, 1970; BeGole et al, 1987) essentially were only able to provide accurate information in two dimensions.

An early attempt at developing a technique to measure tooth movement in three dimensions was initiated by Simons (1924). Simons developed an instrument called the symmetrograph. The symmetrograph was designed so that three axes set at right angles to one another were used to define points on the occlusal surfaces of teeth on dental casts. Following a series of modifications,
Van Der Linden et al (1972) developed an instrument called the Optocom. The Optocom was a type of microscope with two cross hairs made of wire. The microscope was mounted over a table that could be adjusted in two dimensions. On this table, the dental casts were placed and firmly fixed. The microscope was then used to define the position of any given point. Two dimensions were measured with the cast thus in place. To measure the third dimension it was necessary to reorient the cast in a vertical slot. Once the information was gathered it was transmitted to a teletype via a converter and printed out.

Use of the Optocom later by other investigators

(Moyers et al, 1976) identified the problem of accuracy using this instrument because of a lack of depth perception resulting from a monocular eyepiece. As a result of this problem, identification of the exact location of cusp tips had to be aided by marking points on the cast with a pencil. Jones et al (1980) noted that if a change in tooth position was to be measured, then exactly the same points on all measured study casts would have to be accurately located. They suggested using acrylic templates with holes to accurately mark the same positions on each cast.

The usefulness of a new instrument to measure dental casts in three dimensions, the Reflex Metrograph, has been investigated by several researchers (Butcher and Stephens, 1981; Takada et al, 1983; and Richmond, 1987). The cast to be measured was placed in front of a semi-reflecting mirror. Marked points on the dental casts were measured by aligning a movable light source, 0.3 millimeters in diameter, over the points. The light source was carried on a three-dimensional slide system which enabled it to be digitized. Reports on the accuracy of the instrument vary. Butcher and Stephens indicate the magnitude of error to be 0.128 millimeters in the mesio-distal direction, 0.299 millimeters in the vertical direction and 0.353 millimeters in the bucco-lingual direction. On the other hand Takadà et al found that the reading of the points was accurate to within +\- 0.1 millimeters. Richmond claimed the error to be less than 0.27

millimeters.

The Reflex Microscope is a newer refinement of the Reflex Metrograph. Like the Reflex Metrograph, the Reflex Microscope is linked to a microcomputer. This instrument allows for the non-invasive, three-dimensional measurement of a microimage marker in the form of a light spot projected into the field of view. Speculand et al (1988) indicate that this instrument is capable of a measurement error of less than 0.15 millimeters for linear distances.

Despite the relative accuracy of these measuring devices, one problem still remained. As Jones et al (1980) realized, there is still great difficulty in obtaining a stable base to act as a frame of reference when measuring changes in tooth position. In order to obtain meaningful results when studying tooth movement, orientation of sequentially measured casts must be standardized. Duff (1987) and Sonya (1987) developed a method by which they were able to standardize the orientation of the various measured casts. Their method involved the fabrication of orientation splints which were made to fit over the anchor segments of the dental casts. The splints were then used to orient the plaster casts on a measuring apparatus. Using this method, Duff and Sonya were able to obtain accurate measurements of tooth movements in all three dimensions.

2.5 EVALUATION OF FACTORS EFFECTING TOOTH MOVEMENT

Orthodontic tooth movement requires a mechanical force to be applied to a tooth thereby causing a biological response which enables the tooth to move. Because tooth movement would not occur without either of these components it stands to reason that factors that affect both the mechanical force and the biological response would have an effect on tooth movement.

The broad range of acceptable force values reported in the literature eliminates the possibility of drawing any definite conclusions regarding ideal force levels. It does, however, raise certain questions related to the roles of biological and mechanical variability.

Biological variability may include such factors as length or shape of the root (Burstone et al, 1961), the density of the surrounding bone (Reitan, 1985), and the cellular response to the force systems (Burstone et al, 1961; Hixon and Klein, 1972; Reitan, 1985). In fact Kvinnsland et al (1989) applied a continuous force for five days to rat molars to move them mesially. The results indicated a substantial increase in blood flow in the periodontal ligament and the pulp of all areas examined on the experimental side when compared to the control side. Olgart et al (1988) in a similar experiment demonstrated an increase in blood flow in response to load application. Reitan (1957, 1960) suggested that differences in response to different age groups may be a result of changes in the density of the alveolar bone. Adults, he claimed, have fewer bone-forming and bone-resorbing elements in their periodontal ligaments because of a decrease in marrow spaces. Storey (1973) not only supported Reitan but included gender, hormone levels and types, and diet as factors affecting rates of tooth movement.

Recently Germane et al (1989) have demonstrated a tremendous variation in the facial surface contour of teeth of the same type in different patients. The variation in individual anatomy was found to be greater than the differences between the standard bracket slot bucco-lingual angulation prescriptions used in orthodontics. Their research revealed that vertical placement errors of brackets as small as one millimeter can alter bucco-lingual slot angulation values by as much as ten degrees. Thus the type of tooth tipping movement generated by a rectangular wire could be quite significantly altered unless appropriate adjustments were made to the wire.

Burstone (1985) commented on the great role biological variability appears to play in the rate of tooth movement after recognizing great variation in the rate of tooth movement in response to identical force systems. Building on Reitan's observation (1957) of three phases of tooth movement, the initial, the lag and the post-lag phases, Burstone (1962a, 1985) further explained that the rate of tooth movement in response to a given force was different during each stage.

According to Burstone and Reitan the initial phase occurs for a very short period of time immediately after the application of the force. The tooth movement corresponds to the displacement of the tooth through the periodontal membrane space. The second stage, or lag phase, represents a period of time during which alveolar bone resorption occurs. The last stage, or post-lag phase, represents the period of greatest tooth movement as the tooth moves into the area of previously resorbed alveolar bone. The fact that the rate of tooth movement appeared to be different for each phase led Burstone to conclude that the rate of tooth movement was directly related to the cellular components of the system. Burstone did comment, however, that increases of force at the lower levels of activation would increase the rate of tooth movement while increases of force at higher magnitudes would more likely delay tooth movement. He attributed this delay to the process of hyalinization of the periodontal ligament.

The difficulties encountered in obtaining in vivo data make the determination of the actual effect of biological variability on the rate of tooth movement an issue that is not readily resolved. Conversely, the role of mechanical variability on the rate of tooth movement may be slightly easier to deal with because of its more quantifiable nature.

As early as 1917, Fish recognized the importance of being able to determine the types of force systems generated from orthodontic appliances. It was not until 1962 that an instrument capable of measuring both forces and moments of an activated appliance was developed

(Burstone, 1962). Prior to that time, measurements that were made were somewhat crude and were incapable of measuring both forces and moments in more than two dimensions.

The development of more accurate measuring devices resulted in the development of a greater understanding of the mechanical principles of orthodontic appliances. It became apparant that the magnitude and direction of the applied forces could be controlled by altering some of the physical or mechanical properties of the appliances. The load-deflection rate is one such property that can be altered.

Load-deflection rate refers to the amount of force produced for every unit activation of an orthodontic wire or spring (Burstone, 1962). The load-deflection rate can be altered in three ways:

1) load-deflection rate varies directly as the fourth power of the diameter of round wire and as the third power of the depth of rectangular wire;

2) load-deflection rate varies inversely to the third power of wire length; and

3) load-deflection rates differ with different elastic properties of different wire materials.

Although these factors are broadly accepted and understood, the variability of tooth movement in response to appliances that appear similar is still quite great. Possible explanations for this variability include:

1) Inconsistencies encountered at the manufacturing level of wires, brackets, and bands (Burstone et al, 1961;

Hixson et al, 1982; Creekmore, 1979; Raphael et al, 1981; Lang et al 1982);

2) Comparisons of seemingly similar appliances used in friction and frictionless situations (Stoner, 1960; Paulson et al, 1970; Kamiyami and Sasaki, 1972; Newman, 1972; Andrew, 1975; Riley, 1979; Frank and Nikolai, 1980 Adreason and Zwanziger, 1980; Sullivan, 1982; Thurow, 1982; Garner et al 1986);

3) Differences in operator techniques particularly in the fabrication of various appliances (Mahler and Goodwin, 1967; Steyn, 1977; White et al 1979);

4) Differences in size and distance between active and reactive segments (Stoner, 1960; Gianelly and Goldman, 1971).

The reason for such a broad range of acceptable force levels reported in the literature may now be apparent. With so many variables affecting the rate of tooth movement and with the great variability in techniques reported, the body of orthodontic literature does not permit definitive conclusions about the force\biological response\tooth movement milieu.

2.6 FORCE MAGNITUDE - RATE OF TOOTH MOVEMENT STUDIES

The debate on the ideal magnitude of force necessary for orthodontic tooth movement has perpetuated for many years. Farrar (1876) indicated that forces of lighter magnitude were more desirable for tooth movement.

Oppenheim (1911) and Schwartz (1932) suggested that one should avoid forces greater than the capillary blood pressure of the periodontal ligament, 20-26 grams per square centimeter. McKeag (1929) claimed that the initial force for each tooth should be two ounces. Stuteville (1937) argued that the magnitude of an orthodontic force was not as important as the distance through which it was active. Moyers and Bauer (1950) maintained that the ideal orthodontic appliance should operate over a distance of less than 0.2mm with a force of 15-25 grams. Ackerman, Cohen, and Cohen (1966) found that forces between 33-548 grams per square centimeter were sufficient to cause bone resorption in a pigeon. Weinstein (1967) found that muscular forces with values as low as 1.68 grams were capable of moving teeth and that the amount and rate of tooth movement associated with such low forces was significantly smaller in young adults than in adolescents. This concept of biologic variability led Nikolai (1985) to believe that biologic variability was the main reason that one best force-time pattern (or optimal force) for simple tooth displacement does not exist.

The scientific study of the relationship between force magnitude and rate of tooth movement was largely initiated about forty years ago. Storey and Smith (1953) studied the various canine retraction springs used in orthodontics in the early 1950's and realized that a wide range of forces was being used. Upon investigating different pre-calibrated forces, they realized there were differences between the rates of tooth movement for light and heavy forces. With heavy forces, the canines moved very little in the first week or two while the anchor units moved forward. Following this, the canine moved rapidly, and as the force decreased, movement of both canine and anchor teeth slowed. With a light force, tooth movement was rapid at first and then slowed. If the distance of tooth movement was plotted as a function of time, the difference between the total amount of tooth movement seen with light and heavy forces was negligible. It was noticed, however, that with heavy forces much more anchor tooth movement occurred. When tooth movement was plotted against the average weekly load applied to the canine teeth, it appeared as though there was an optimum range of force required to induce a maximum rate of tooth movement. This finding naturally lead to the question of integrating the corresponding tissue changes with the known force. In fact Storey quickly acknowledged that it was no the force applied to the crown of the tooth but the pressure at the bone\tooth interface that was important.

Storey and Smith (1952) indicated that ideally between 150-250 grams was necessary for the translation of cuspids with only negligible movement of the anchor teeth. For forces below this optimum range there was practically no movement of the cuspid tooth. While they did note that cuspid teeth always moved by tipping at the apical third of the root, this study did not take into account the differing amounts of tipping among the various teeth measured. As Reitan (1957) points out, in bodily movement the force is applied over a much larger area than in tipping movement. Hence in bodily movement the same force will yield a lighter pressure or load on the periodontal membrane. Accordingly Storey and Smith could more ideally have correlated the different amounts of tipping with the different "optimal" forces observed. In light of the work of Storey and Smith and the theories later proposed by Reitan (1957) and Burstone (1962) (that three different rates or phases of tooth movement occurred over the activation period) the rate of tooth movement can be seen not only as a result of a change in force but also as a function of time.

Understanding the relationship between stress and the rate of tooth movement is enhanced by consideration of three stages of tooth movement. Burstone (1962) and Reitan (1957) categorize these stages as the initial phase, the lag phase and the post-lag phase. In the initial phase, tooth movement is very rapid, likely due to the distortion or strain of the supporting periodontal structures. The lag phase, which can last several weeks follows a few days later during which no tooth movement is observed. In this stage, Reitan observed that the histology of the periodontal ligament revealed hyalinization. Before tooth movement can resume the hyalinized periodontal ligament must be resorbed. The degree of hyalinization has been noted to be associated with the magnitude of the stress in the ligament (Yoshikawa, 1981). With light forces, only small areas of hyalinization occur and these are quickly resorbed; with heavier forces, larger areas of hyalinization occur and therefore take longer to resorb. Tooth movement resumes at a rapid rate in the post-lag phase. Histologically, undermining resorption of the adjacent bone has removed the hyalinized region while osteoclasts spread over a wide surface area directly resorb the boney surface facing the periodontal ligament.

Thus it is apparent that the rate of tooth movement, as a function of force or stress, is different for the various stages. The influence of force magnitude and its decay as tooth movement occurs in affecting the duration of these stages has not been determined.

Begg (1965) suggests that the optimum force, the force to provide maximum biologic response and the maximum rate of tooth movement is 300 grams for canines. Forces above this cause the canine to operate as the anchor tooth while the desired anchor tooth, the posterior tooth, moves rapidly. These higher forces apparently alter the biochemical turnover of the bone cells and periodontal ligament so as to reduce the rate of tooth movement. Jarabak and Fizzell (1963) state that the most effective pressures are between 2 and 25 grams per millimeter squared of projected area. Lee (1965) fashioned a study after Storey and Smith (1952) and concluded that the range of optimum force levels fell between 150-260 grams. Utley (1968) used cats to determine the distance and rate of tooth movement occurring in response to different magnitudes of force. In his study, the forces ranged from 40-560 grams and were determined by precalibrating stretched latex elastics. Superimposing radiographic tracings of the right and left maxillary jaw sections was the means by which he measured tooth movement. He concluded that the maxillary cuspids of both the right and left side of the same animal moved equal distances regardless of the different magnitudes of force which were delivered to the right and left appliances. He also conlcuded that the rate of cuspid tooth movement was not related to the magnitude of force delivered by the appliance and that each animal exhibited its own individual rate of tooth movement.

Hixon et al (1969) scrutinized the existing theory of tooth movement. He noted that "...While the concept of an optimal force has a ceratin physiologic appeal, we could find no data to support such a theory when data were analyzed on a clinically useful time scale - even when the problem of variation in tipping was omitted." In a later study (Hixon et al, 1970), he used an appliance system with a more uniform stress distribution throughout the periodontal ligament. Six patients were monitored over an eight week period. The conclusion was that, although heavier forces seemed to move teeth at a greater rate, the individual metabolic response was so variable that it overshadowed any differences caused by force magnitude. He also observed that teeth showing translatory movement were displaced at a slower rate than teeth that were tipped.

Fortin (1971) used dogs to 1) determine the correlation between the magnitude of the force and the anchorage loss and 2) to consider the rate of tooth movement. A force of 146 grams (proportional to a force of 450 grams applied on a human canine for translation) was determined as being optimal in terms of tissue response and tooth movement. Histologically, he found direct bone resorption, numerous blood vessels were numerous on the pressure side and very few areas of hyalinization. Fortin concluded that a very low stress level was present all along the root during bodily movement. Furthermore, he found that the only difference between the responses to light and heavy forces was the severity of root resorption which was markedly greater following the application of heavy forces.

The debate over the magnitude of optimum force effective for optimum movement continued. The hypothesis that a continuous light force is most effective for optimum tooth movement (Storey and Smith, 1952; Burstone, 1961) was tested by Paulson (1970). Using laminographic superimpositions Paulson demonstated a complete absence of mesial movement of the maxillary first molars during cuspid retraction. His study pointed out that the inevitability of molar anchorage loss need not be accepted.

Boester and Johnston (1974) identified the need for an analysis of the response of various force magnitudes both within and among individuals. They conducted a clinical investigation to compare rates of tooth movement at four different force levels, 2,5,8, and 11 ounces.

Their results indicated that the two-ounce force produced significantly less tooth movement than the 5,8, and 11 ounce forces. The higher forces produced about the same amount of space closure at the same rate. They also found that relative anchorage loss was independent of the force employed and therefore did not support the differential force concept.

Ziegler and Ingervall (1989) compared the rate of tooth movement using sliding mechanics and a canine retraction spring. They reported that the canine was retracted faster and with less distal tipping with the spring than with the sliding mechanics. Their data also revealed that the rate of cuspid retraction averaged 1.91 millimeters distally per month using the canine retraction spring which was precalibrated to apply 160 grams of force. In addition, they showed an average of 4.5 degrees of distal tipping and 30 degrees of rotation of the cuspid when using the retraction spring. Their analysis, however, only describes the movement of the crown and does so in only two dimensions.

Nikolai (1975), in an attempt to understand why there had been a debate over whether or not an optimum force existed, mathematically analyzed in two dimensions orthodontic force systems. He suggested that for an optimum force theory to be realistic it must take into account the influence of the following parameters:

1. tooth root surface area and shape;
2. the type of tooth movement desired with its

particular pattern of distributed forces transmitted to the periodontal ligament;

3. magnitude-time pattern of the crown force system to be applied - continuous or intermittent; and

4. individual biology (tissue response).

He concluded, that despite the controversy, further study to develop the optimum force theory could prove to be valuable.

Pedersen et al (1990) built a model of an experimental tooth to which they applied differential force systems. To measure displacement, two strain gauge bridges were constructed and mounted at two specific points on the experimental tooth. Their results indicated that the type of tooth movement was not affected by the magnitude of the force. Their results were not in keeping with the results of Pryputniewicz and Burstone (1979) who found that the center of rotation was displaced apically when higher loads were applied to teeth tested <u>in vivo</u>. One of the primary reasons for the contrast in the results may stem from the fact the Pederson's experiment only looked at tooth movement in two dimensions while Pryputniewicz and Burstone examined tooth movement in three dimensions.

The common denominator in all the above studies appears to be a lack of accurate three-dimensional determination of the force values actually applied and the tooth displacement achieved. As a result tremendous variation has been observed. A complete understanding of the principles involved can only be gained if a three-dimensional assessment is made both in terms of the forces applied and the movement of the teeth in question. Without this analysis, individual biologic variabilty will continue to be used to explain the variations seen in tooth movement as result of similar force systems.

As Quinn and Yoshikawa (1985) point out, the studies most commonly referenced in this area have three major problems which complicate the clinical studies of force magnitude and tooth movement. First, the type of tooth movement (ie. tipping or translation) has not been adequately controlled. Second, because of the nonlinear, time-dependent course of tooth movement following appliance activation, measurements of tooth movement that are not coordinated with activation can systematically bias the data. Third, the large measurement errors, as well as the large variation in the rate of tooth movement make statistically significant findings difficult to interpret.

The technique developed by Duff (1987) and Sonya (1987), based in part on the force measuring system developed by Paquien (1978) and Lack (1980), has demonstrated a method whereby tooth movement in response to known forces can be correlated. The technique og Duff and Sonya, with some modifications, served as the technical basis of this study in which the relationship between force and the rate of tooth movement (velocity) was investigated.

2.7 SUMMARY

Over the past few decades much speculation has been made regarding the optimal force level required for ideal tooth movement. The large range reported in the literature can partially be explained by the difficulty in obtaining quantitative data. Essentially what is necessary is:

1) a means of analyzing tooth movement in three dimensions (antero-posteriorly, bucco-lingually, and occluso-gingivally);

2) a means of simultaneously measuring forces and moments in three dimensions;

3) knowing how the applied force system changes as the tooth moves.

Combining the technique developed by Duff (1987) and Sonya (1987) with the machine developed by Paquien (1978) for measuring force systems, it is possible to study the rate of tooth movement in response to known applied force systems. Examination of the temporal inter-relationship between tooth movement and the consequent changes in the force system would make it possible to get one step closer to understanding the significance of the concept of optimal force level in orthodontic mechanotherapy.

3. METHODS AND MATERIALS

3.1 INTRODUCTION

To determine the rate of tooth movement in response to a known applied force system four patients were selected from the screening programme at the University of Manitoba on the basis of their need for cuspid retraction. Cuspid retraction was the tooth movement chosen for this study for the following reasons:

1. Cuspid retraction is a common procedure in orthodontics that requires the tooth to move over relatively large distances. As a result, the measurement of tooth movement can more readily be detected and measured with a smaller percent error.

2. Translation, or bodily movement is often the type of tooth movement desired.

Because of the difficulty involved in obtaining _in vivo_ data regarding both tooth movement and applied force systems, both _in vivo_ and _in vitro_ techniques were utilized in this study. In the _in vivo_ phase, tooth movement in response to pre-tested activated appliances was monitored. The _in vitro_ phase consisted of measurements of the activated appliances and measurements of tooth movements using accurate study casts. It was possible to examine the rate of tooth movement in response to known force systems because of the frequency with which the measurements were made. An attempt was made to monitor each patient three times per week for a period of six to eight weeks in order to retrieve the appropriate data.

Complete descriptions of both the _in vivo_ and _in vitro_ phases are given below.

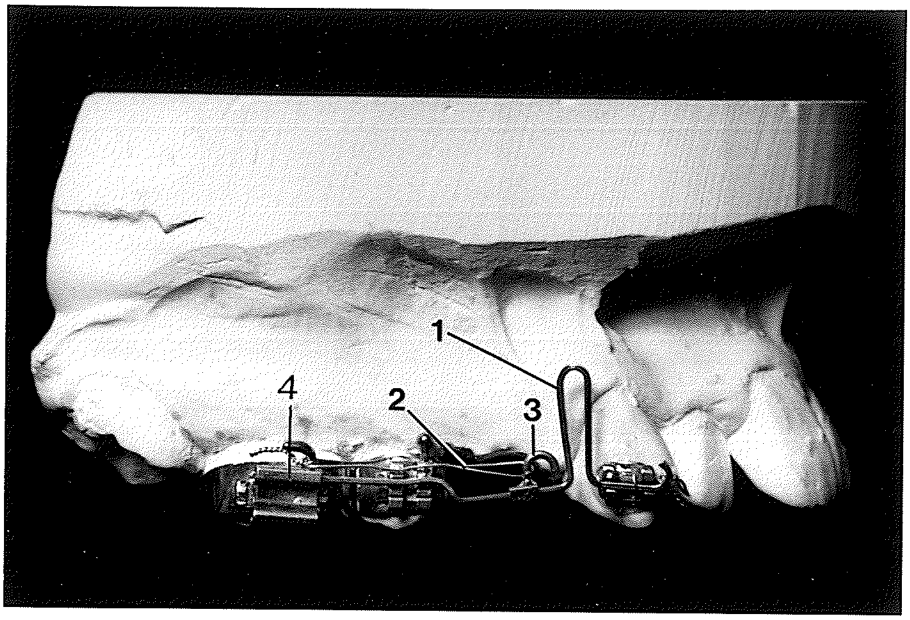
3.2 DESCRIPTION OF _IN VIVO_ PHASE

A total of four patients were selected, yielding a total of seven maxillary cuspids retracted for this study. Although the data were collected and analyzed for all seven cuspids, the data from three were not used in drawing final conclusions. Omission of two cupsids from the final analysis was primarily because of technical problems related to the anatomy of these teeth. The third cuspid was omitted because of a total lack of movement of this tooth during the experimental phase of treatment.

Each patient had "A" Company bands placed on the first molars and bicuspids and Ormco brackets placed on the cuspids. Both brackets and bands had 0.018" x 0.025" slot sizes. In all but the one patient (D.R.) who only had one cuspid retracted for this study, maxillary second molars were banded using compatible "A" company bands. Maximum anchorage in the posterior segments was achieved by the insertion of a Nance-TPA appliance along with the insertion of a passive arch segment connecting the posterior teeth. This arch segment was made of 0.017" x 0.025" stainless steel. In the one case in which second permanent molars were not banded it was possible to include the first bicuspid and cuspid on the contralateral side in the posterior anchor segment thereby increasing the anchorage. Once the anchor units were established and the first bicuspids extracted, the patients were left untreated for four months. This lapse in time allowed the extraction sites to fill in with bone thereby ensuring that the measured tooth movement was in fact through bone. In addition this four month lapse in time ensured passivity of the fabricated arch segments prior to the initiation of loop activation.

Vertical loops made of 0.018" x 0.018" stainless steel were fabricated for each patient. Figure 3.1 demonstrates a typical vertical loop in vitro. The loops were activated by tying a stainless steel ligature around a hook crimped immediatley distal to the vertical loop and the hook on the molar band. Two identical loops were made for each cuspid in the event that the original loop should become distorted or lost.

The length of each loop was determined by estimating the height of the center of resistance of the cuspids in question. The height of the cuspids was estimated by the use of radiographs. Determination of the center of resistance of the tooth was based on the assumption that the center of resistance of a single rooted tooth is approximately one third to one half of the root length apical to the alveolar crest (Burstone and Pryputniewicz, 1980). Anatomical restrictions such as sulcus height and frenal attachments were also taken into consideration



1. Active vertical loop.
2. Tie back ligature.
3. Tie back hook.
4. Auxiliary tube.

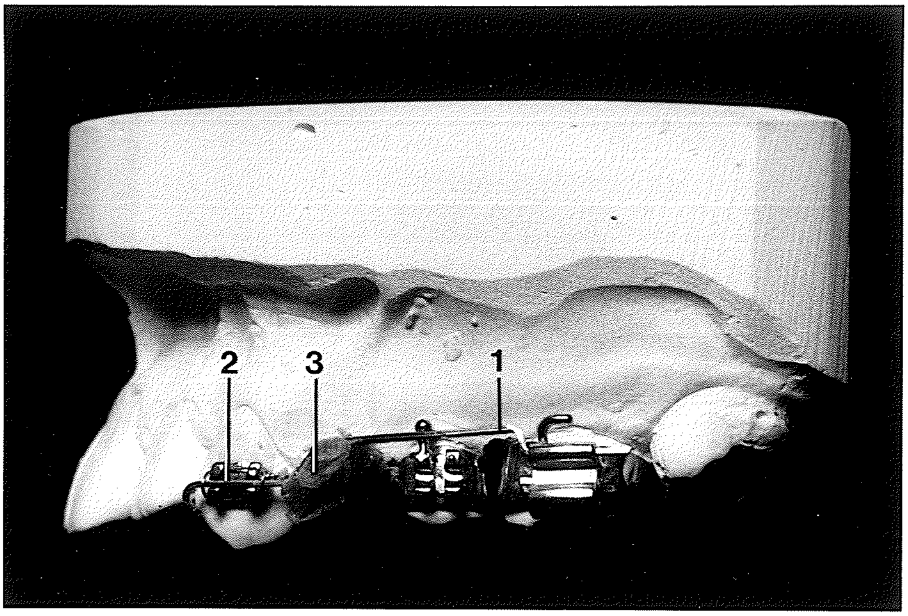
Figure 3.1 Typical vertical loop *in vitro*.

during loop fabrication.

At the time of insertion of the loops, both the original and the duplicate loops were adapted so that they accurately fit the auxillary tube on the molar band and the cuspid bracket passively. In most cases this adaptation involved incorporating first order bends mesial to the vertical loop. These bends were placed to minimize unwanted buccal movements. At this time the duplicate loop was properly labelled and safely stored.

To accurately test the appliances in vitro it was necessary to replicate the precise relationship of the molar and cuspid bracket positions in vivo to the in vitro setting. Prior to the ligation and activation of the cuspid retraction appliance a precise record of the relative positions of the cuspid and molar brackets. The procedure outlined below made it possible to relate the bracket positions in vitro to simulate the tooth positions in vivo.

The record of the bracket positions in vivo was made with the fabrication of a wire template. The template consisted of two separate lengths of 0.018" x 0.018" stainless steel wire. One end of each of the two lengths of wire was made to fit passively into the slots of the molar band and cuspid bracket respectively. To prevent the wires from sliding in the slots and to ensure an accurate fit of the template, a small half helix was bent into the anterior section of wire and placed against the mesial wing of the cuspid bracket. For similar reasons a small gable bend was place in the posterior section of the



1. Posterior section of passive template.
2. Anterior section of passive template.
3. Helices joined with acrylic resin.

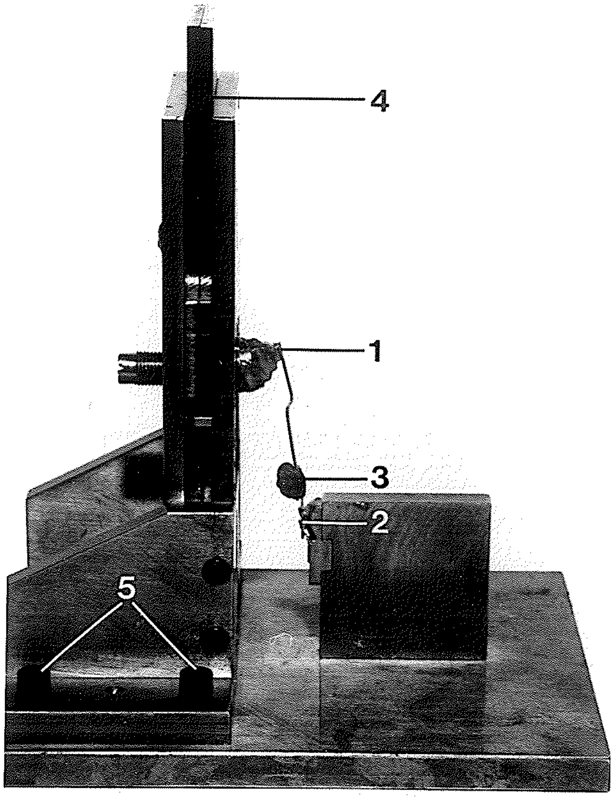
Figure 3.2 View of passive wire template *in vitro*.

In order to determine the amount of activation in the appliance at each visit, the distance between the parallel arms at the base of the loop was measured at each appointment using a Boley gauge.
The actual forces and moments present at any given time were later determined after measurements were taken from each loop on the measurement apparatus.

3.3 DESCRIPTION OF *IN VITRO* PHASE

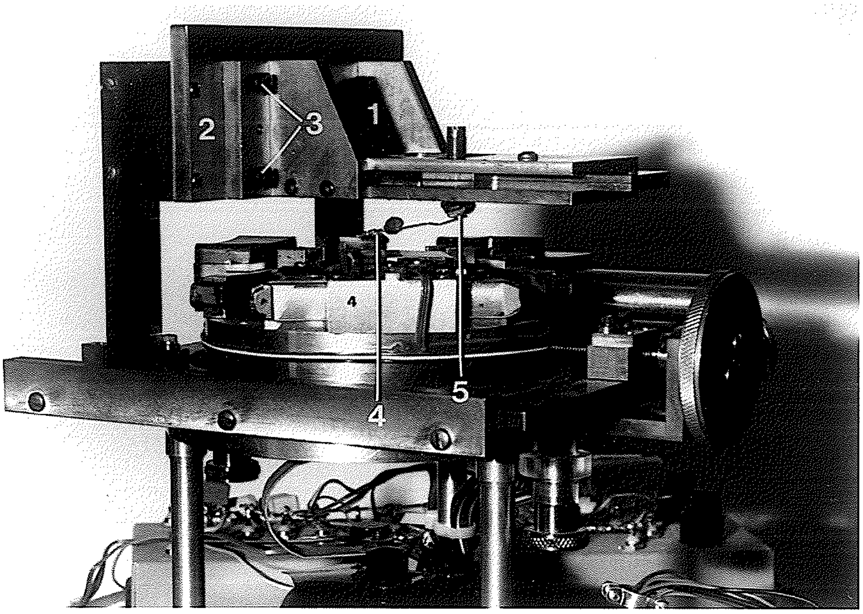
The passive wire template described in the previous section was used to accurately determine the positions of the simulated cuspid and molar teeth and their respective bracket and band on the measuring apparatus. This procedure was facilitated by using a specially designed frame which was capable of fitting over the measuring apparatus. Figure 3.3 demonstrates the use of the transfer jig attached to the frame while Figure 3.4 demonstrates the way in which the frame and transfer jig fit on the measuring apparatus.

The final position of the simulated cuspid tooth was fixed in the same position it would occupy on the measuring apparatus. An 0.018" x 0.025" bracket was bonded to the machine tooth of the transfer jig. The molar machine tooth was represented by a screw with a removable machined end which had been contoured to approximate the buccal surface of an upper first molar



1. Molar tube bonded to adjustable screw.
2. Cuspid bracket bonded to removable metal section.
3. Template representing <u>in vivo</u> bracket position.
4. Adjustable metal plates.
5. Securing screws.

Figure 3.3 Bracket positioning transfer jig.



1. Transfer jig.
2. Support frame.
3. Securing screws.
4. Cuspid bracket secured to center of measuring apparatus.
5. Molar tube.

Figure 3.4 Transfer jig attached to frame on measuring apparatus.

tooth. An 0.018" x 0.025" tube was bonded to this machined tooth. This machined tooth could be adjusted in all three dimensions or six directions.

The passive wire template was then securely tied into the cuspid bracket on the frame. The adjustable screw and the machined end of the molar tooth were then bonded together in such a way that the end of the template passively fit the slot on the tooth in a way that replicated the positions of the teeth and the brackets *in vivo*. Once the transfer frame was set-up in this manner, the template was removed and the loop was secured in place. At that point the entire transfer apparatus was taken to the measuring apparatus. (See Figure 3.4).

Once the loop was secured in place so that it represented the *in vivo* situation *in vitro*, a zero reading was taken. The loop was then activated in the same manner and to the same degree as it had been *in vivo* and the data regarding the force and moment characteristics were collected during controlled steps of deactivation. The reported data displays the units of force measured in grams rather than in Newtons. The selection of these units was made in order to be in keeping with what is conventional in the orthodontic literature. The amount of activation differed for each patient ranging from 1.8 millimeters to 4.0 millimeters. A description of the measuring apparatus is provided in Appendix A.

3.4 MEASUREMENT OF CHANGES IN TOOTH POSITION

In order to measure the changes in tooth position from one cast to another it was necessary to choose stable references. Selected points on the teeth in the posterior anchor segments containing the passive arch wires were chosen as the references for this study along with one palatal rugae for each patient. Three widely spaced points were placed on each tooth including the cuspids. The points were spaced as far apart as possible on each tooth in an attempt to minimize measurement error . The precise location of the points on each tooth of each subsequent cast was facilitated by the use of custom-made acrylic tooth templates which were placed over the teeth. These tooth templates had holes drilled in them so that pencil marks could be placed on the tooth upon which they were placed (Figure 3.5).

To understand the precise nature of the tooth movements it was necessary to examine tooth movement in all six dimension (three linear, three rotational). In order to do this, an axis system with three mutually perpendicular axes had to be defined. Figure 3.6 represents the axis system used for this study.

Linear movement of the teeth along the x-axis which is conventionally defined as mesial or distal was defined as either anterior or posterior movement in this study. Likewise, what has conventionally been described as buccal and lingual tooth movement for movement along the z-axis

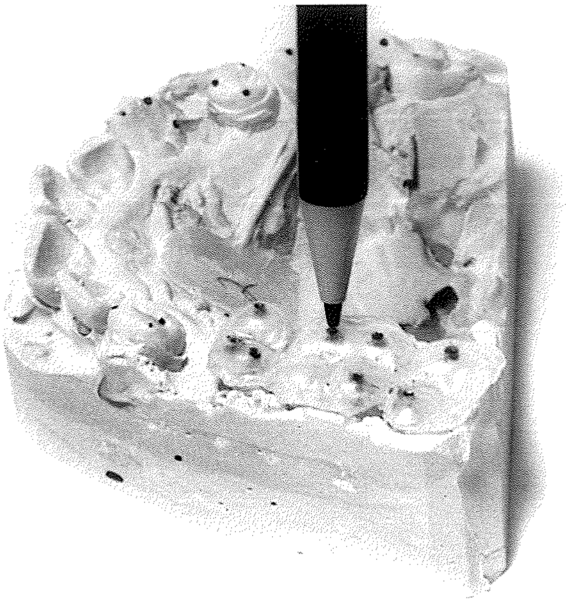
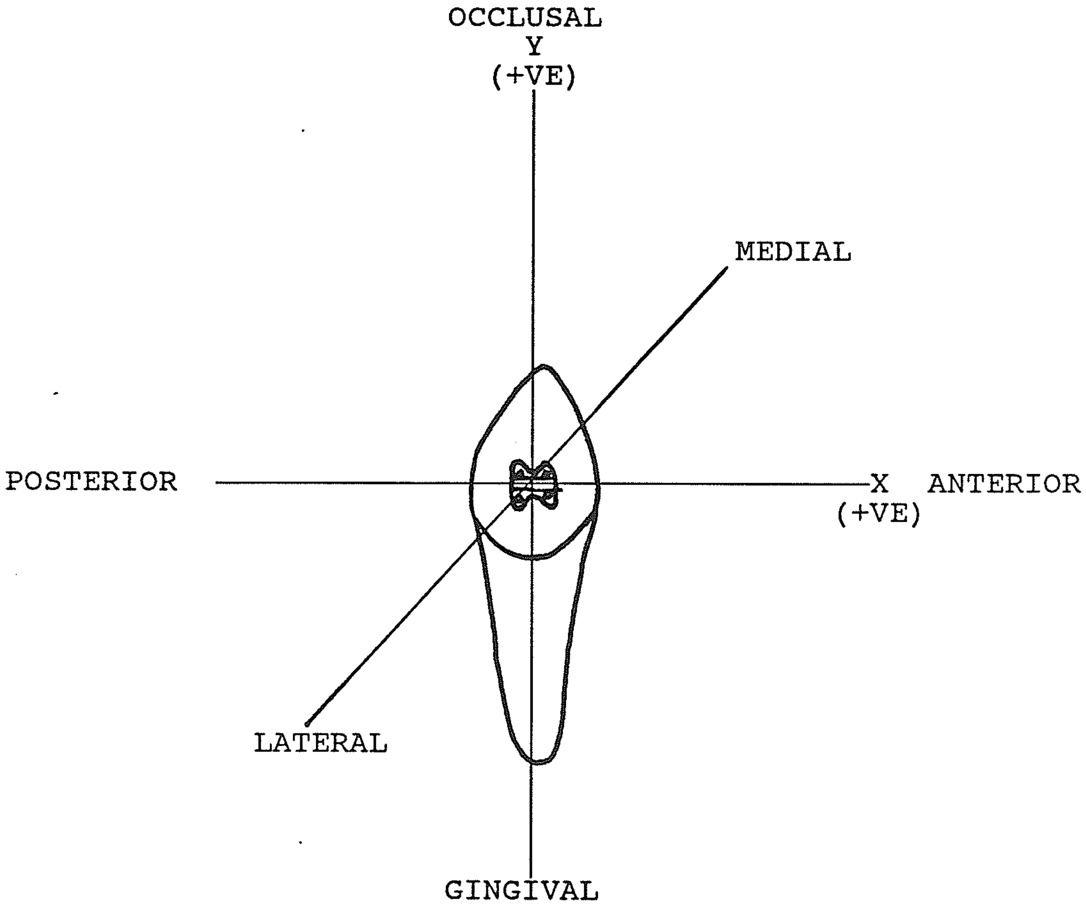


Figure 3.5 Plaster cast with acrylic template and marking pencil in position.

Figure 3.6 Axis system used to define direction of tooth movement. (Tooth #23)

Note: Reverse medial and lateral for tooth #13.

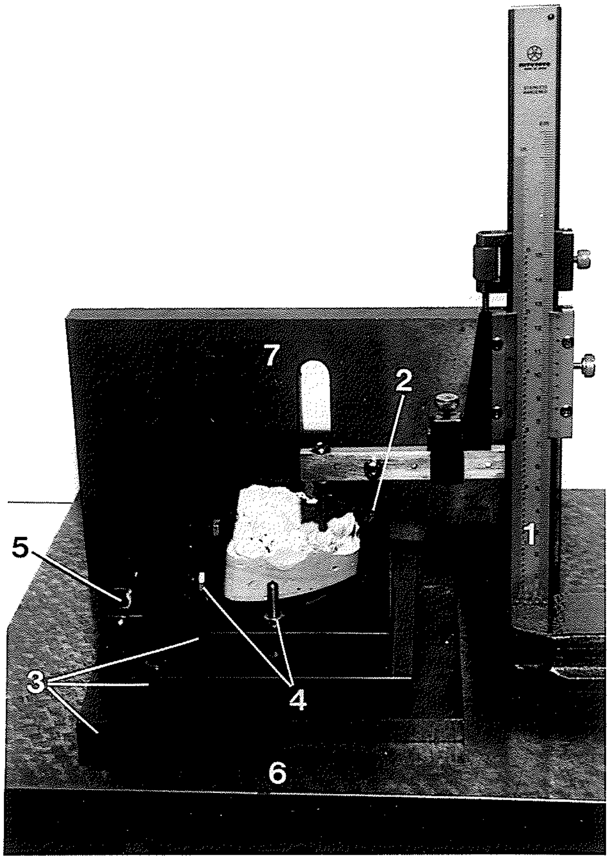


has been replaced with medial and lateral tooth movement. The redefinition of these directions of tooth movement more accurately describes the actual movement seen when measured on a perpendicular axis system. Linear movements along the y-axis are described as occlusal and gingival movements.

Once the casts were appropriately marked, changes in tooth position were ready to be measured. To meausre the reference points in all three dimensions, the casts were placed on the measuring apparatus which consisted of three machined metal baseplates. The measuring apparatus was capable of being adjusted in all three dimensions. This apparatus was then placed on a precisely machined metal table with a fixed perpendicular metal plate (Figure 3.7).

Three reference points, one of which was the palatal rugae, were chosen for each patient to aid in the standardizing of the levelling of the casts. Once the casts were firmly fixed in the measuring apparatus by a securing screw the occluso-gingival measurements of these points were taken using a Vernier height gauge (Figure 3.7). The relative heights of these three points was standardized from cast-to-cast for each patient to ensure that the bases were levelled.

After the levelling procedure, the various points on the casts were measured relative to the machined metal baseplate using the Vernier height gauge. This measurement instrument had an inherent accuracy of 0.01 millimeter. The initial measurements with the base of the casts parallel to the machined metal table were



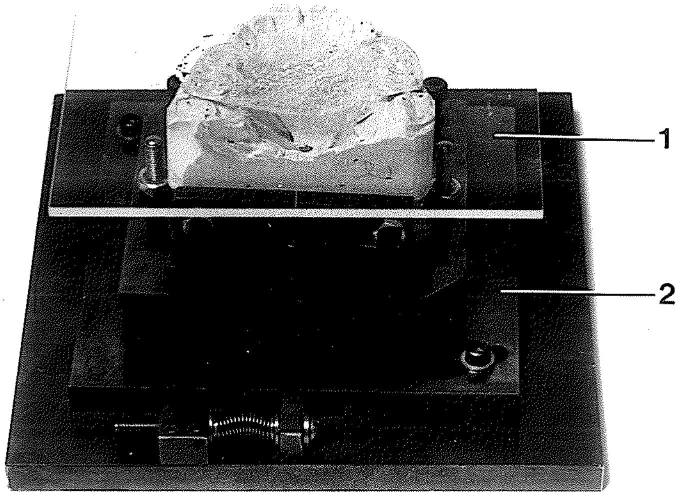
1. Vernier height gauge.
2. Screw to secure cast.
3. Adjustable baseplate assembly.
4. Securing screws.
5. Adjustment screws.
6. Machined metal table.
7. Perpendicular metal back plate.

Figure 3.7 Apparatus used for measuring tooth position.

measurements in the occluso-gingival direction.

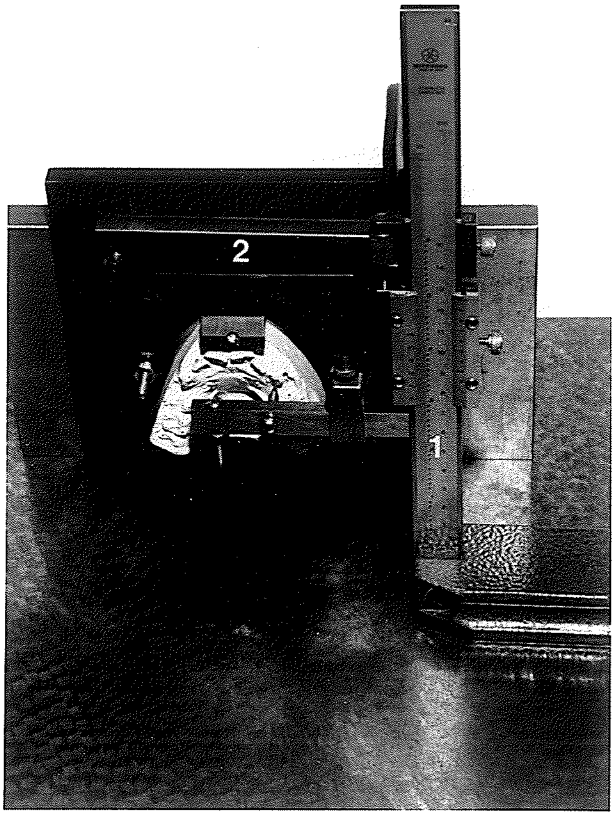
To obtain measurments in the other dimensions with this method, the fabrication of an orientation splint was required. This splint was fabricated from rigid acrylic on the Biostar Vacuform machine using casts that were taken just prior to the activation of the appliances. The splint covered only the cusp tips of the anchor teeth with all other teeth being fully relieved. This splint was trimmed and fixed to a piece of square rigid acrylic (12.5cm x 12.5cm x 3mm). Perpendicular lines were then scribed on this square section of acrylic (Figure 3.8). The use of this splint depended on solid anchor units so that they could be used for reference points. The orientation splint was then placed onto the cast and the entire apparatus was turned through 90 degrees so that it was now fixed against the perpendicular backplate of the machined table (Figure 3.9). To ensure that the measurements taken on the following casts within the same patient were oriented in the same manner, the horizontal scribe line on the orientation splint was made to be parallel with the horizontal machined table. Adjustable screws on the machined metal baseplate assembly facilitated this orientation. Measurements of the points marked on the casts taken with the cast oriented in this manner were in the antero-posterior dimension relative to the metal base plates.

To measure the points in a medio-lateral dimension, the baseplate apparatus was turned 90 degrees on the perpendicular backplate (Figure 3.10). Once again the



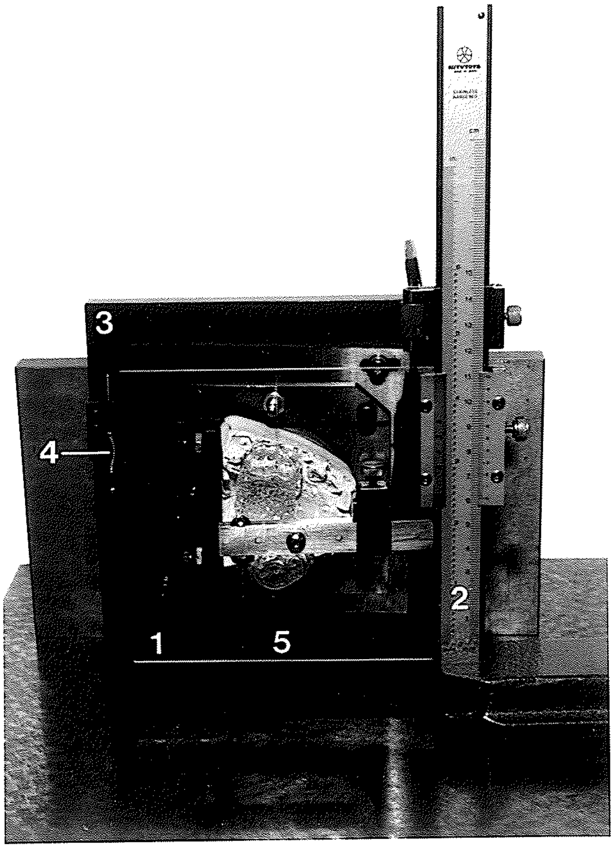
1. Acrylic orientation splint.
2. Adjustable baseplate assembly.

Figure 3.8 Plaster cast in baseplate assembly with orientation splint.



1. Vernier height gauge.
2. Adjustable baseplate assembly.

Figure 3.9 Cast positioned for measuring reference points in antero-posterior plane.



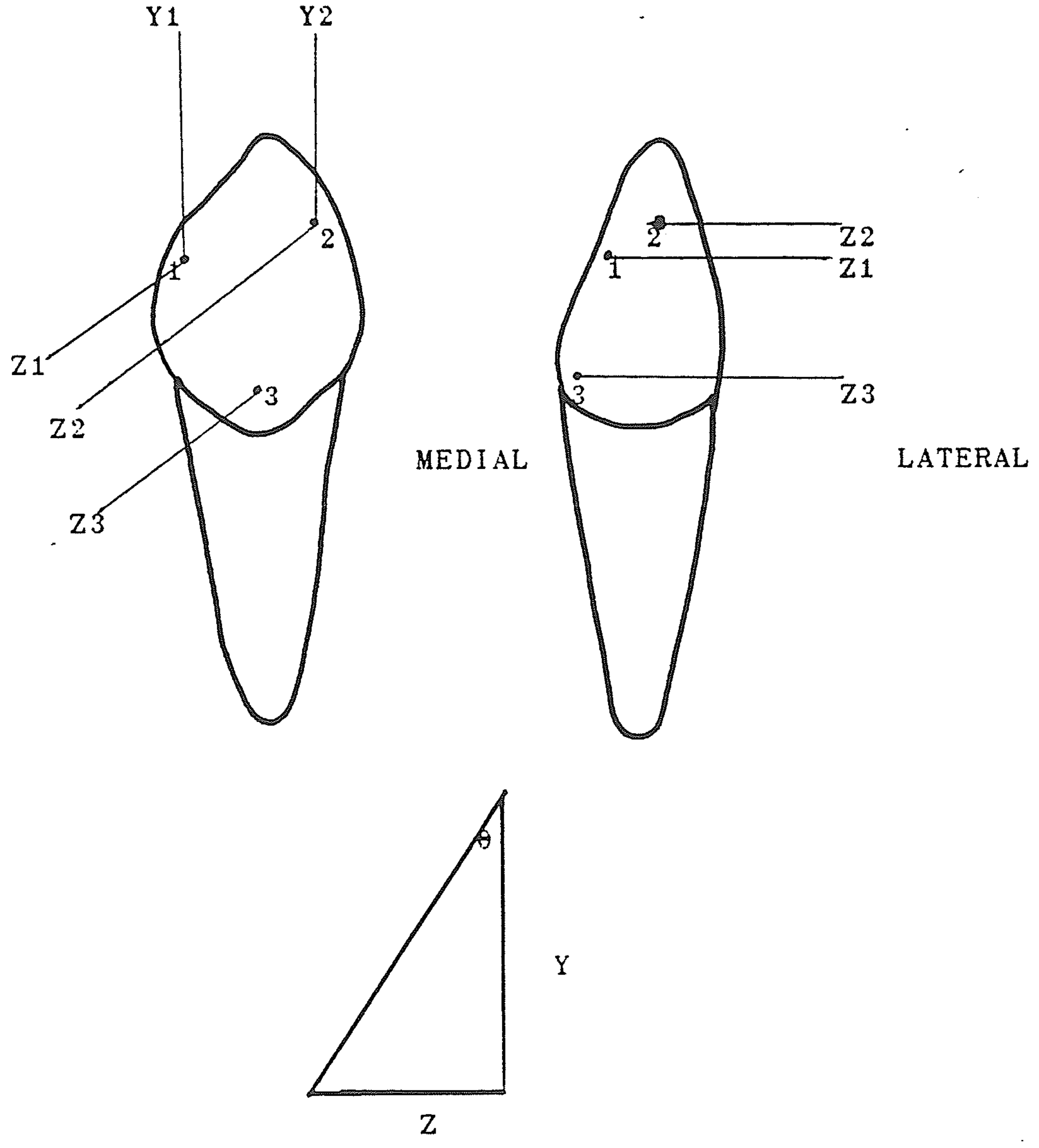
1. Orientation splint.
2. Vernier height gauge.
3. Adjustable baseplate assembly.
4. Adjustment screw.
5. Cross-scribed lines on orientation splint.

Figure 3.10 Cast positioned for measuring reference points in transverse plane.

orientation of the casts was verified by means of the now horizontal scribe line on the orientation splint and measurements made relative to the machined metal baseplate.

To determine the changes in linear tooth positions, the changes in the reference points on subsequent casts were compared to the original pre-activation cast in each dimension for each patient. This method involved the averaging of the reference points to give an estimate of the actual position of a reference point on the crown of the cuspid. To determine the changes in angular measurements, measurements taken in two dimensions were necessary. For example, to determine the rotation around the x-axis or medio-lateral tip, the occluso-gingival distance between points 1 and 2 were averaged and the distance from this new point to point 3 was calculated. In the z-axis, the distance between points 1 and 2 were averaged and the difference between this "point" and point 3 was calculated. Thus, these two calculated distances form mutually perpendicular sides of a right-angled triangle the hypotenuse of which is a consistent statement of the angle of tip of the tooth around the A-P axis. This angle determined the original position of the tooth in this dimension. To determine the change in tooth position, this same procedure was followed for each subsequent cast and compared with the original position. The difference between the two angles represents the change in tooth movement. Figure 3.11 illustrates how

Figure 3.11 Calculation of angular measurements used to assess change in tooth position using medial-lateral tip as an example.



$$\theta x = \tan^{-1}\left[\left\{\frac{(Z1 + Z2)}{2} - Z3\right\} \Big/ \left\{\frac{(Y1 + Y2)}{2} - Y3\right\}\right]$$

The change in the angle is given by:

$\theta n - \theta 1 = \Delta\theta$ For n = number of casts.

these angles were determined. The two other angular measurements were determined similarly.

The collection of the data in such a manner enabled an accurate quantitative measurement of <u>in vivo</u> tooth movement to be performed <u>in vitro</u>. Measurements of subsequent casts taken three times per week from the same patient enabled tooth movement to be studied over the course of several weeks.

It is apparent from the descriptions given in this chapter that this project involved numerous components. These components can be summarized by the following brief descriptions of each procedure:

1. The selection and application of known applied force systems to several patients in whom cuspid retraction was necessary.
2. The <u>in vitro</u> reproduction of the <u>in vivo</u> tooth bracket positions permit testing of the appliances.
3. The testing of the appliances in three dimensions in the <u>in vitro</u> setting.
4. The monitoring of the activation of the appliances <u>in vivo</u> along with a record of changes in the tooth positions over short periods of time.
5. Measurement of the actual change in tooth positions over time using plaster casts.
6. Correlation of tooth movement with known applied force systems over a given time period.

4.RESULTS

4.1 INTRODUCTION

Analysis of the results rendered in this project will focus on the data collected from three patients: B.J., J.B., and D.R. Both the maxillary right and left cuspids will be analyzed in patient B.J. while only the maxillary left cuspids will be analyzed in patients J.B. and D.R. An attempt to retract the maxillary right cuspid in patient J.B. was made, however, the final results indicate that the cuspid underwent negligible movement and therefore analysis of this tooth movement was omitted. Possible explanations for the lack of movement of this tooth will be presented in the next chapter. In patient D.R. only the left maxillary cuspid was retracted for this study because of anatomical constraints encountered with the maxillary right cuspid.

The results are presented in graphic form for each cuspid with linear and rotational tooth movements plotted in millimeters (Figures 4.1A, 4.2A, 4.3A, and 4.4A) and in degrees (Figures 4.1B, 4.2B, 4.3B, and 4.4B) as a function of time.

It should be noted when reviewing the results that the measurements and impressions were not taken at equally spaced time intervals. Additionally, all measurements were made in reference to a true antero-posterior, medio-lateral axis system. Thus, it is not unusual for the tooth in question to exhibit an apparently large rotational component when its movement is following the curve of the dental arch. Lastly, the changes in tooth position have been measured relative to the initial tooth position. References made to tooth position are actuall indicative of crown position.

Results from both the right and left cuspids of patient R.Z. were obtained but will not be presented here. The anatomy of both of these teeth caused difficulties in the gathering of reliable tooth movement data. Recommendations are made in the following chapter for the elimination of such a problem in future work.

An explanation and discussion of the results presented in this chapter will be given in the following chapter.

4.2 COMBINED RESULTS FROM TOOTH MOVEMENT AND LOOP ANALYSIS

4.2.1 PATIENT B.J. - MAXILLARY LEFT CUSPID (#23)

Tooth movement of the maxillary left cuspid (#23) in this patient was followed for 59 days. The loop was activated 4.0mm on day one and remained with 1.7mm of activation on day 59. Despite the fact that the deactivation of the loop would indicate a net posterior movement of 2.3mm, measurements of tooth movement indicate that the tooth moved posteriorly 1.2mm. An explanation for this occurence along with explanations for the remainder of the results can be found in the next chapter. On day 32 the left tie-back ligature was found to be loose and was retied with the same amount of activation estimated to be present at the time the ligature became loose.

The results shown in Figure 4.1A and Table 4.1A indicate that the desired tooth movement, cuspid retraction, was achieved with a net movement of 1.20mm posteriorly. At several points in the displacement plot in Figure 4.1A it appears as though the cuspid actually moved anteriorly with respect to its previous position ie. day 18 through to day 32, day 41, day 46, and day 59. As previously mentioned, the ligature wire was noticed to be loose on day 32 and had to be retied. This incident may in part explain the apparent anterior movement from day 18 to day 32.

Figures 4.1A and 4.1B: Linear and angular displacement of tooth #23 in patient BJ.

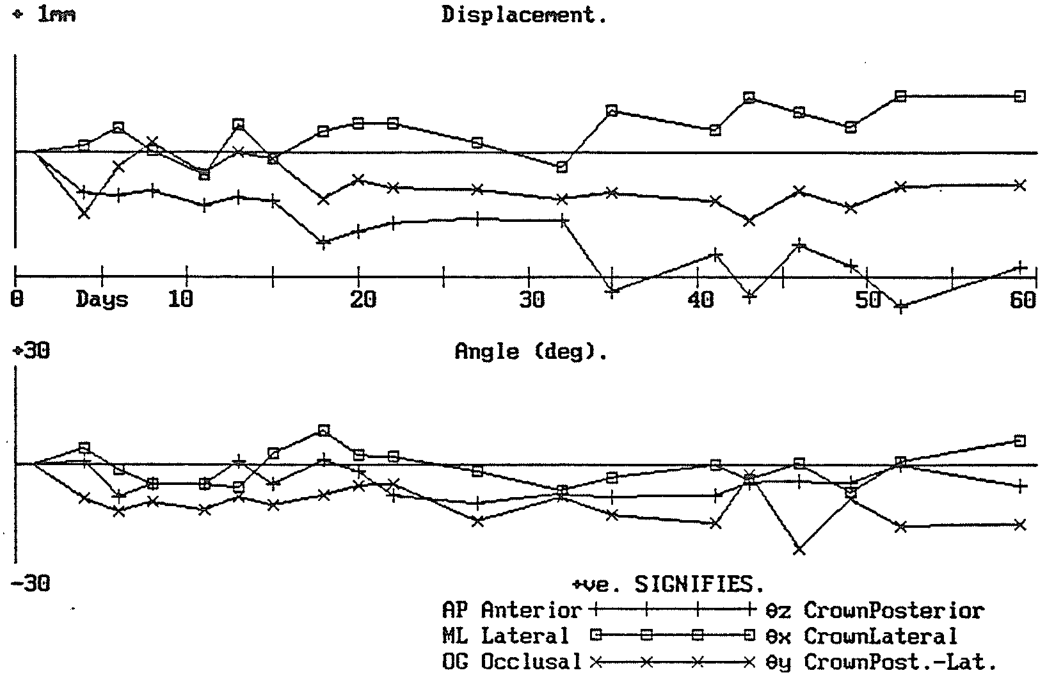


Table 4.1A: Linear and angular measurements for tooth #23 in patient BJ.

CAST#	DAY#	AP	Tz	ML	Tx	OG	Ty
1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	4.00	-0.41	0.94	0.08	5.11	-0.64	-10.04
3.00	6.00	-0.44	-9.56	0.26	-1.52	-0.15	-14.08
4.00	8.00	-0.40	-5.60	0.02	-6.01	0.10	-11.09
5.00	11.00	-0.56	-5.69	-0.23	-5.94	-0.21	-13.89
6.00	13.00	-0.47	1.02	0.29	-6.87	-0.00	-9.96
7.00	15.00	-0.51	-5.64	-0.07	3.77	-0.06	-12.25
8.00	18.00	-0.95	1.47	0.22	10.44	-0.49	-9.25
9.00	20.00	-0.83	-1.68	0.31	2.91	-0.29	-6.06
10.00	22.00	-0.75	-9.30	0.31	2.76	-0.36	-5.77
11.00	27.00	-0.69	-11.95	0.11	-1.81	-0.39	-17.37
12.00	32.00	-0.70	-8.77	-0.16	-7.57	-0.48	-9.85
13.00	35.00	-1.44	-9.69	0.44	-3.85	-0.41	-15.32
14.00	41.00	-1.06	-9.19	0.25	0.32	-0.51	-17.75
15.00	43.00	-1.51	-5.24	0.59	-4.30	-0.71	-2.72
16.00	46.00	-0.95	-4.91	0.43	0.60	-0.41	-25.48
17.00	49.00	-1.18	-5.45	0.27	-8.13	-0.57	-10.29
18.00	52.00	-1.61	0.38	0.59	1.18	-0.35	-18.55
19.00	59.00	-1.20	-6.20	0.60	7.66	-0.33	-18.04

DISTANCES
AP,ML,OG in mm.

ANGLES
Tx,Ty,Tz in degrees

+ve. SIGNIFIES.

AP Anterior	Tz CrownPosterior
ML Lateral	Tx CrownLateral
OG Occlusal	Ty CrownPost.-Lat.

Figure 4.1A also demonstrates that there was a net lateral movement of the cuspid of 0.60mm and a net gingival movement of 0.33mm. Initially the cuspid did seem to experience a series of fluctuating lateral and medial movements with a definite trend towards lateral movement toward the final stages of activation. Throughout the course of the 59 days the occluso-gingival movement tended to favour a greater amount of gingival movement but some fluctuation occluso-gingivally was also noted.

The force characteristics of the loop in each of the three dimensions over the period of activation can be seen in Table 4.1B. This loop was activated to a distalizing force level of 278g on day one and remained with a distalizing force of 106g on day 59 at the termination of the project. The forces in the other two dimensions remained considerably lower with a maximum force of -56g gingivally and 27g laterally.

Figure 4.1B is a plot of the tipping and rotatory movements of the left cuspid of patient B.J. The cuspid appears to undergo a series of movements whereby it is alternating between tipping anteriorly and posteriorly within a +\- 12 degree range. The initial tipping movement is in the posterior direction and is followed by a rather marked anterior tipping movement of the crown.

The related moment values seen in Table 4.1B indicate that between -1,013g-mm and -403g-mm were present at the center of resistance on day one through to day 59. The moment values for this patient were based on the

TABLE 4.1B: B.J. - FORCE CHARACTERISTICS OF THE LOOP USED FOR TOOTH #23 OVER THE PERIOD OF ACTIVATION

CAST #	DAY	ACTIVATION (mm)	Px	Py	Pz	Mx	My	Mz
			(grams)			(gram-millimeters)		
1	1	4.0	278	-56	27	-156	-1577	-1013
2	4	2.7	188	-36	16	-128	-1068	- 697
3	6	2.7	188	-36	16	-128	-1068	- 697
4	9	2.7	188	-36	16	-128	-1068	- 697
5	11	2.7	188	-36	16	-128	-1068	- 697
6	13	2.7	188	-36	16	-128	-1068	- 697
7	15	2.7	188	-36	16	-128	-1068	- 697
8	18	2.7	188	-36	16	-128	-1068	- 697
9	20	2.7	188	-36	16	-128	-1068	- 697
10	22	2.7	188	-36	16	-128	-1068	- 697
11	27	2.7	188	-36	16	-128	-1068	- 697
12	32	3.0	204	-42	19	-232	-1232	- 788
13	35	2.7	188	-36	16	-128	-1068	- 697
14	41	2.4	157	-32	14	- 65	- 948	- 605
15	43	2.3	149	-31	14	- 72	- 938	- 575
16	46	2.3	149	-31	14	- 72	- 938	- 575
17	49	2.1	133	-29	13	- 85	- 917	- 512
18	52	1.7	106	-23	9	- 85	- 768	- 403
19	59	1.7	106	-23	9	- 85	- 768	- 403

assumption that the distance from the bracket to the center of resistance for this tooth was 10mm. Negative moment values at the center of resistance indicate a tendency for the crown to tip posteriorly.

Figure 4.1B also demonstrates the rotation (Oy) around the long axis of the tooth and the medio-lateral tipping (Ox). Rotation occurred throughout the 59 day period in a postero-medial direction to a maximum of 25.48 degress on day 46. The maximum rotation around the x-axis was 10.44 degrees indicating a lateral movement of the crown. This maximum medial crown rotation (or tip) around the x-axis occurred on day 18 which corresponds with the beginning of the previously mentioned anterior movement of the cuspid. With the exception of this rotation, reasonable control in the medio-lateral tip of this tooth movement was achieved.

Table 4.1B also presents the moment values for the moments around the x and y axes. While the moment values around the x-axis are minimal, the moment values around the y-axis range from -1,577 g-mm to -768 g-mm during the period of activation. A large moment value such as this would tend to indicate a tendency towards a net posterior-medial rotation around the y-axis.

The rate of tooth movement over the observation period is charted for all four patients in Table 4.5. The rate of tooth movement for each phase of tooth movement along with an overall rate of tooth movement is given. The overall rate of tooth movement is based on a 28 day cycle, the average time between visits for orthodontic patients undergoing treatment. The overall rate of tooth movement in an antero-posterior direction for tooth #23 in patient B.J. was 0.57 millimeters per 28 days.

4.2.2 PATIENT B.J. - MAXILLARY RIGHT CUSPID (#13)

Tooth movement of the maxillary right cuspid (#13) was followed for 59 days in patient B.J. The loop was activated 3.5mm on day one and remained with 1.6mm of activation on day 59. On day 35 the tie-back ligature on this cuspid was loose and it was retied.

The results of the measured tooth movement show that this cuspid was retracted posteriorly with a net movement of 1.42mm (Figure 4.2A and Table 4.2A) while the difference in the activation of the loop indicates a change of 1.9mm. As with the left cuspid of the same patient, there were several times during the procedure that the cuspid appeared to be moving anteriorly with repsect to its previous position ie. days 13, 18, 27, 35, 49, and 52. Again, a loose ligature may explain the anterior movement at day 35.

Figure 4.2A demonstrates that there was a net lateral movement of the cuspid of 1.08mm and a net gingival movement of 0.18mm. From day 13 to day 27 this cuspid tended to experience a net medial movement when compared to its original position. Although the tooth appeared to have some fluctuation in both the occlusal and gingival directions ranging from 0.51 millimeters

Figures 4.2A and 4.2B: Linear and angular displacement of tooth #13 in patient BJ.

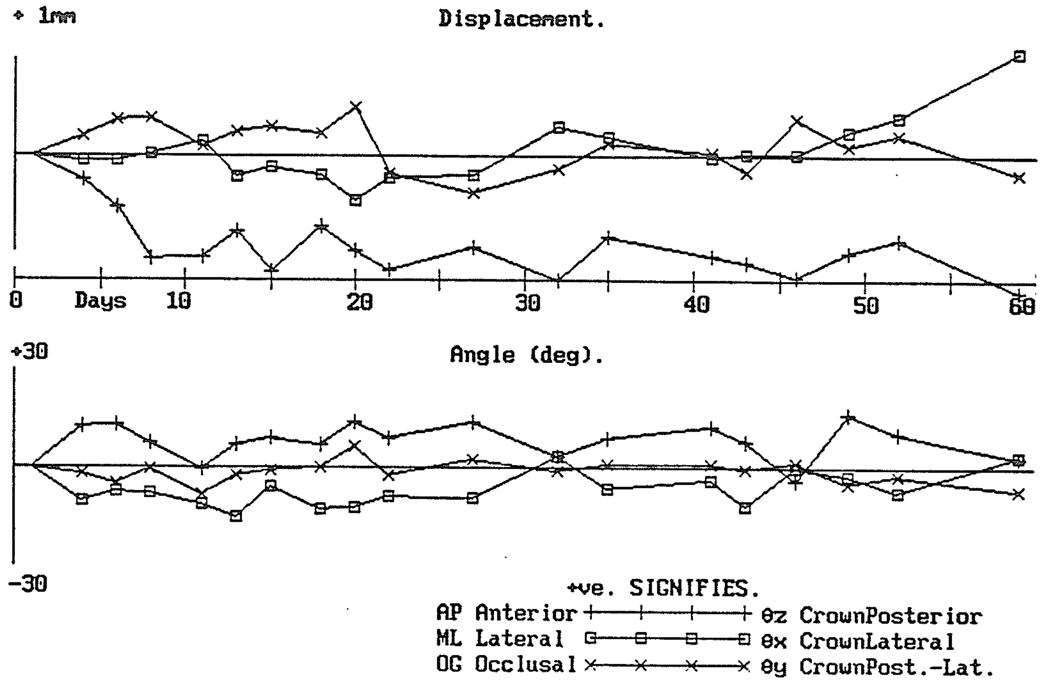


Table 4.2A: Linear and angular measurements for tooth #13 in patient BJ.

CAST#	DAY#	AP	Tz	ML	Tx	OG	Ty
1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	4.00	-0.25	12.50	-0.05	-10.17	0.21	-1.85
3.00	6.00	-0.54	12.86	-0.05	-7.25	0.38	-4.96
4.00	8.00	-1.07	7.71	0.02	-7.67	0.39	-0.50
5.00	11.00	-1.06	-0.47	0.15	-10.99	0.10	-8.50
6.00	13.00	-0.79	7.17	-0.21	-15.26	0.26	-2.34
7.00	15.00	-1.22	9.22	-0.11	-5.82	0.31	-0.90
8.00	18.00	-0.74	6.87	-0.19	-12.51	0.24	0.31
9.00	20.00	-0.99	13.94	-0.48	-12.34	0.51	6.79
10.00	22.00	-1.19	8.89	-0.23	-8.83	-0.18	-2.20
11.00	27.00	-0.96	14.15	-0.20	-9.26	-0.39	2.70
12.00	32.00	-1.30	3.78	0.30	3.38	-0.13	-0.61
13.00	35.00	-0.84	9.24	0.20	-6.37	0.14	1.22
14.00	41.00	-1.04	12.40	-0.01	-3.84	0.03	1.35
15.00	43.00	-1.11	8.17	0.01	-11.55	-0.16	-0.59
16.00	46.00	-1.26	-3.79	0.02	0.39	0.40	1.47
17.00	49.00	-1.00	16.40	0.25	-2.48	0.10	-4.99
18.00	52.00	-0.87	10.43	0.41	-7.30	0.23	-2.54
19.00	59.00	-1.42	3.12	1.08	3.61	-0.18	-6.81

DISTANCES
AP,ML,OG in mm.

ANGLES
Tx,Ty,Tz in degrees

+ve. SIGNIFIES.

AP Anterior	Tz CrownPosterior
ML Lateral	Tx CrownLateral
OG Occlusal	Ty CrownPost.-Lat.

occlusally to 0.34 millimeters gingivally, the final tooth position did not differ markedly from its original position in this dimension.

The force characteristics of the loop in each of the three dimensions over the period of activation can be seen in Table 4.2B. This loop was activated to a force level of 215g in the posterior direction on day one and remained with a posterior force of 65g on day 59 at the completion of the project. The transverse (lateral) force level remained quite low with a maximum force of 38g on day one. Vertically the maximum force level was -99g on day one. A negative force in the vertical direction indicates a gingival force. The magnitude of force in this direction may be somewhat larger than expected.

Figure 4.2B is a plot of the tipping and rotatory movements of the right cuspid of patient B.J. Initially the cupsid tipped posteriorly. This movement was followed by an uprighting of the tooth. Only at two points during the 59 days (days 11 and 46) did the crown actually tip more anteriorly than it had been at day one.

Rotation around the long axis initially resulted in the crown rotating postero-medially. Rotation around this axis fluctuated between small rotations postero-medially to small rotations postero-laterally. The final position of the tooth was a postero-medial rotation of the crown. The range of the rotation around this axis was +\- 8.50 degrees. Rotation around the x-axis, or medio-lateral tip started with an initial

TABLE 4.2B: B.J. - FORCE CHARACTERISTICS OF THE LOOP USED FOR TOOTH #13 OVER THE PERIOD OF ACTIVATION

CAST #	DAY	ACTIVATION (mm)	Px	Py	Pz	Mx	My	Mz
				(grams)		(gram-millimeters)		
1	1	3.5	215	-99	38	- 35	-689	-951
2	4	2.9	153	-65	32	- 48	-474	-707
3	6	2.8	145	-61	31	- 66	-451	-679
4	8	2.8	145	-61	31	- 66	-451	-679
5	11	2.5	120	-49	28	-120	-382	-594
6	13	2.5	120	-49	28	-120	-382	-594
7	15	2.5	120	-49	28	-120	-382	-594
8	18	2.5	120	-49	28	-120	-382	-594
9	20	2.4	113	-45	27	-121	-353	-564
10	22	2.4	113	-45	27	-121	-353	-564
11	27	2.3	93	-38	23	-124	-296	-503
12	32	2.2	93	-38	23	-124	-296	-503
13	35	2.0	86	-31	21	-126	-239	-444
14	41	2.2	100	-38	23	-124	-296	-503
15	43	2.0	86	-31	21	-126	-239	-444
16	46	2.0	86	-31	21	-126	-239	-444
17	49	2.0	86	-31	21	-126	-239	-444
18	52	1.6	65	-19	18	-110	-226	-230
19	59	1.6	65	-19	18	-110	-226	-230

rotation of the crown medially. Throughout the 59 day period much of the net effect of this rotation remained in a medial direction although at several points a net lateral crown tip was observed ie. days 32, 46, and 59.

The related moment values to account for the tipping movement around the z-axis can be seen in Table 4.2B. These values indicate that the moment present at the center of resistance between days 1 through 59 was between -951g-mm and -230g-mm therefore indicating a tendency for the tooth to tip posteriorly. These moment values are based on the assumption that the distance from the bracket to the center of resistance was 10mm.

The moment values around the x-axis indicate a very narrow and minimal range. The moment values around the y-axis range from -689g-mm to -225g-mm during the period of activation. A moment in this direction would have a tendency to rotate the tooth postero-medially.

The overall rate of tooth movement for tooth #13 in patient B.J. was 0.67 millimeters per 28 days. The rates of tooth movement for each phase are summarized in Table 4.5.

4.2.3 PATIENT J.B. - MAXILLARY LEFT CUSPID (#23)

Tooth movement of the maxillary left cuspid (#23) in this patient was followed for 43 days. The loop was activated 1.8mm on day one and was reactivated on day 29

1.4mm. Prior to reactivation on day 29 0.9mm of activation remained. The final amount of activation remaining on day 43 was 0.4mm. This amount of activation would suggest that the cuspid moved a total of 1.9mm - 0.9mm from the first activation and 1mm from the second activation. The measured posterior tooth movement indicated that this tooth actually moved 1.03mm after the first activation and 0.09mm after the second activation for a total of 1.12mm. The results given below are based on the complete 43 day period.

The results indicate that this cuspid had a net posterior movement of 1.12mm, a net lateral movement of 1.3mm and a net gingival movement of 0.19mm (Figure 4.3A and Table 4.3A). On days 13, 29, 36, and 43 the cuspid appears to have moved slightly anteriorly with respect to its previous position. Movement in the lateral direction appears to have been fairly consistent, again with slight movements from lateral to medial between days 8 to 13. The cuspid did experience a series of both occlusal and gingival movements with a maximum movement of 0.19mm occlusally and 0.37mm gingivally.

The corresponding force values for the loop used in this patient can be seen in Table 4.3B. The maximum force in the posterior direction was 228g on day one. 171g of force in this direction was delivered after the second activation on day 29. The forces tapered off to 105g and 46g after the first and second activations respectively. The forces in the lateral and gingival directions were fairly minimal ranging from 19 to 5g and -50 to -11g

Figures 4.3A and 4.3B: Linear and angular displacement of tooth #23 in patient JB.

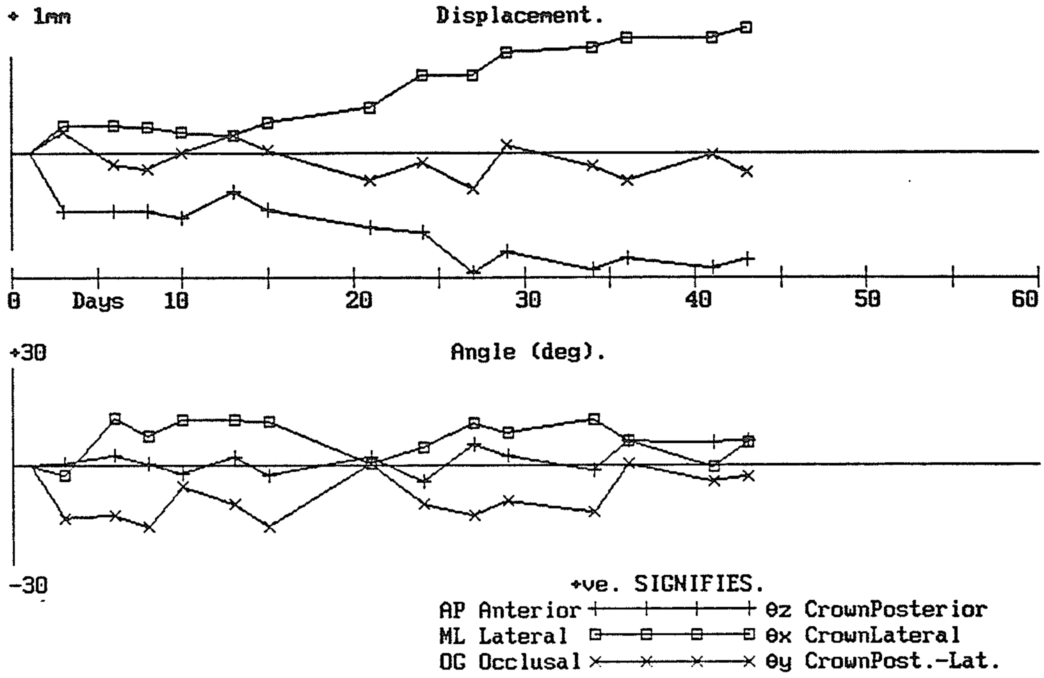


Table 4.3A: Linear and angular measurements for tooth #23 in patient JB.

CAST#	DAY#	AP	Tz	ML	Tx	OG	Ty
1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	3.00	-0.61	0.64	0.29	-3.02	0.23	-16.39
3.00	6.00	-0.60	3.35	0.28	14.73	-0.12	-15.23
4.00	8.00	-0.60	0.63	0.27	8.86	-0.16	-18.43
5.00	10.00	-0.66	-2.32	0.22	14.18	0.00	-6.22
6.00	13.00	-0.40	2.76	0.19	13.91	0.19	-11.63
7.00	15.00	-0.58	-2.96	0.32	13.51	0.04	-18.80
8.00	21.00	-0.77	2.63	0.48	0.71	-0.29	0.49
9.00	24.00	-0.82	-4.92	0.81	5.72	-0.09	-11.69
10.00	27.00	-1.25	6.77	0.82	12.79	-0.37	-15.26
11.00	29.00	-1.03	3.31	1.04	10.07	0.09	-10.76
12.00	34.00	-1.22	-1.26	1.10	13.82	-0.13	-14.29
13.00	36.00	-1.10	7.62	1.21	7.69	-0.29	0.60
14.00	41.00	-1.20	7.17	1.20	-0.22	-0.01	-5.01
15.00	43.00	-1.12	7.36	1.30	6.85	-0.19	-3.48

DISTANCES
AP,ML,OG in mm.

ANGLES
Tx,Ty,Tz in degrees

+ve. SIGNIFIES.

AP Anterior	Tz CrownPosterior
ML Lateral	Tx CrownLateral
OG Occlusal	Ty CrownPost.-Lat.

TABLE 4.3B: J.B. - FORCE CHARACTERISTICS OF THE LOOP USED FOR TOOTH #23 OVER THE PERIOD OF ACTIVATION

CAST	DAY	ACTIVATION	Px	Py	Pz	Mx	My	Mz
#		(mm)		(grams)			(gram-millimeters)	
1	1	1.8	228	-50	19	76	-767	-840
2	3	1.4	171	-37	16	26	-599	-664
3	6	1.4	171	-37	16	26	-599	-664
4	8	1.3	157	-35	14	32	-547	-603
5	10	1.3	157	-35	14	32	-547	-603
6	13	1.3	157	-35	14	32	-547	-603
7	15	1.3	157	-35	14	32	-547	-603
8	21	1.0	118	-31	13	38	-427	-439
9	24	0.9	105	-30	13	38	-393	-388
10	27	0.9	105	-30	13	38	-393	-388
11	29	0.9	105	-30	13	38	-393	-388
11*	29	1.4	171	-37	16	26	-599	-664
12	34	1.0	118	-31	13	38	-427	-439
13	36	0.9	105	-30	13	38	-393	-388
14	41	0.7	82	-24	11	84	-265	-300
15	43	0.4	46	-11	5	50	-120	-170

*Reactivation of the loop.

respectively.

Figure 4.3B is a plot of the tipping and rotatory movements of the left cuspid of patient J.B. The plot indicates that the cuspid underwent a series of tipping and uprighting movements within a +\- 7 degree range. The initial tipping movement of the crown was in a posterior direction. The final position of the tooth was also with the crown tipped posteriorly with respect to its initial position. During the course of treatment the corresponding moments ranged from -840g-mm to -170g-mm. The moment values for this patient were based on the assumption that the distance from the bracket to the center of resistance was 9mm. The final rotatory position of the cuspid was one in which it had rotated postero-medially 3.48 degrees. Although the net rotation on day 43 was quite small, postero-medial rotations as large as 18 degrees were noted on days 8 and 15.

The cuspid also experienced a significant and consistent lateral crown tip with a net lateral crown tip of approximately 7 degrees. The medio-lateral tip ranged from 3.02 degrees medially to almost 15 degrees laterally.

On the one hand, the moments generated by the appliance around the x-axis were small. On the other hand, the moment around the y-axis ranged from -767g-mm to approximately -120g-mm. The moment around this axis is likely due to the compensatory bend placed in the loop to ensure its initial passivity.

The overall rate of tooth movement for tooth #23 in patient J.B. was 0.99 millimeters per 28 days. The rates of tooth movement for each phase can be found in Table 4.5. For patient J.B. the calculated rate of tooth movement was based on the initial activation only (ie. from day one through to day 29).

4.2.4 PATIENT D.R. - MAXILLARY LEFT CUSPID (#23)

Tooth movement of the maxillary left cuspid (#23) was followed for 50 days. The loop was activated 2.0mm on day one and remained with 0.2mm of activation on day 50. The amount of deactivation of this loop would indicate that this tooth moved 1.8mm posteriorly when in fact it was actually measured to have moved 1.28mm posteriorly. The tie-back ligature was loose and had to be retied on days 13 and 27.

A net posterior movement of 1.28mm was achieved over the 50 day period (Figure 4.4A and Table 4.4A). During the activation period, the cuspid appeared to move anteriorly with respect to its previous position on days 8, 15, 27, 36, and 41. Very slight anterior movements were noticed on days 43 and 45.

The cuspid also experienced a net lateral movement of 1.42mm and a net occlusal movement of 0.22mm There were several occasions upon which the cuspid appeared to experience a medial movement relative to the previous recorded position. This contrary movement may, in some instances, be explained by a rotational component of tooth

Figures 4.4A and 4.4B: Linear and angular displacement of tooth #23 in patient DR.

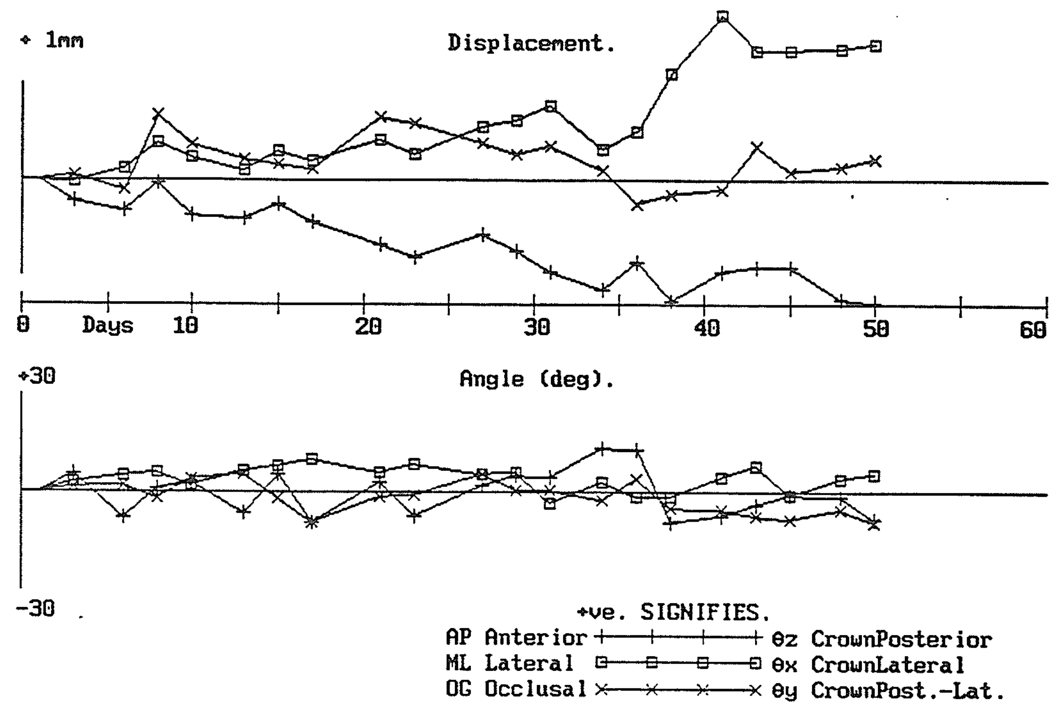


Table 4.4A: Linear and angular measurements for tooth #23 in patient DR.

CAST#	DAY#	AP	Tz	ML	Tx	OG	Ty
1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
2.00	3.00	-0.21	5.62	-0.02	3.08	0.05	1.78
3.00	6.00	-0.31	-7.53	0.12	4.91	-0.10	2.21
4.00	8.00	-0.03	1.24	0.39	6.06	0.67	-1.81
5.00	10.00	-0.36	3.01	0.24	2.03	0.37	4.21
6.00	13.00	-0.40	-6.19	0.11	6.75	0.22	5.61
7.00	15.00	-0.25	5.67	0.32	8.28	0.17	-1.70
8.00	17.00	-0.44	-9.37	0.21	9.92	0.12	-9.48
9.00	21.00	-0.68	3.04	0.42	6.25	0.67	-1.52
10.00	23.00	-0.81	-7.03	0.28	8.36	0.59	-0.80
11.00	27.00	-0.58	2.25	0.56	5.77	0.40	5.41
12.00	29.00	-0.74	5.17	0.63	6.26	0.28	0.84
13.00	31.00	-0.96	4.82	0.78	-3.44	0.36	0.60
14.00	34.00	-1.15	13.41	0.32	3.23	0.11	-2.10
15.00	36.00	-0.87	12.80	0.52	-1.47	-0.26	4.16
16.00	38.00	-1.26	-9.22	1.12	-1.26	-0.14	-5.01
17.00	41.00	-0.97	-7.06	1.73	4.41	-0.10	-5.28
18.00	43.00	-0.90	-3.97	1.36	8.29	0.36	-7.29
19.00	45.00	-0.91	-0.99	1.35	-0.95	0.09	-8.24
20.00	48.00	-1.25	-1.36	1.38	4.27	0.14	-5.13
21.00	50.00	-1.28	-8.15	1.42	5.50	0.22	-9.48

DISTANCES
AP,ML,OG in mm.

ANGLES
Tx,Ty,Tz in degrees

+ve. SIGNIFIES.

AP Anterior	Tz CrownPosterior
ML Lateral	Tx CrownLateral
OG Occlusal	Ty CrownPost.-Lat.

movement which was greater than the lateral component thereby creating the effect of a net medial movement.

Occluso-gingivally the cupsid did experience some fluctuation in both directions. The maximum occlusal movement was 0.67mm and the maximum gingival movement was 0.26mm. The final position of the tooth, however, was only 0.22mm more occlusal than its original position. Plots of the displaced tooth movement in all three dimensions can be seen in Figure 4A.

The force characteristics of the loop in each of the three dimensions over the period of activation can be seen in Table 4B. This loop experienced an initial activation of 285g in the posterior direction on day one and remained with a force of 28g on day 50. The forces in the other dimensions remained fairly low with a maximum force of -25g gingivally and 35g laterally.

Figure 4.4B is a plot of the tipping and rotatory movements of the left cuspid of patient D.R. The cuspid appears to undergo a series of movements whereby the crown is initially tipping posteriorly immediately followed by a tip in the anterior direction. This tooth underwent a series of anterior and posterior tipping cycles within the range of +\- 13.5 degrees. A noticable prolonged tip in the posterior direction was seen to transpire from days 27 to 36.

The related moment values seen in Table 4.4B indicate that between -1,089g-mm to -117g-mm were present at the center of resistance of the tooth between days one and 50. These moments values have been calculated based

TABLE 4.4B: D.R. - FORCE CHARACTERISTICS OF THE LOOP USED FOR TOOTH #23 OVER THE PERIOD OF ACTIVATION

CAST #	DAY	ACTIVATION (mm)	Px	Py	Pz	Mx	My	Mz
			(grams)			(gram-millimeters)		
1	1	2.0	285	-25	35	168	-851	-1089
2	3	1.6	225	-22	26	148	-695	- 865
3	6	1.6	225	-22	26	148	-695	- 865
4	8	1.6	225	-22	26	148	-695	- 865
5	10	1.6	225	-22	26	148	-695	- 865
6	13	1.6	225	-22	26	148	-695	- 865
7	15	1.3	181	-17	21	59	-534	- 715
8	17	1.3	181	-17	21	59	-534	- 715
9	21	1.3	181	-17	21	59	-534	- 715
10	23	1.4	196	-19	23	89	-588	- 765
11	27	1.5	210	-21	25	119	-641	- 815
12	29	1.1	152	-14	18	38	-444	- 607
13	31	0.9	123	-11	15	55	-371	- 492
14	34	0.8	109	-10	13	63	-335	- 433
15	36	0.8	109	-10	13	63	-335	- 433
16	38	0.8	109	-10	13	63	-335	- 433
17	41	0.6	82	- 8	11	0	-241	- 331
18	43	0.3	42	- 4	6	- 53	-100	- 175
19	45	0.2	28	- 3	3	- 43	- 55	- 117
20	48	0.2	28	3	3	- 43	- 55	- 117
21	50	0.2	28	3	3	- 43	- 55	- 117

on the assumption that the distance from the bracket to the center of resistance is 8mm.

Figure 4.4B also demonstrates a rotation of 9.48 degrees postero-medially at the conclusion of the 50 days. Throughout the 50 day period the rotation fluctuated from postero-lateral to postero-medial. The medio-lateral tipping ranged from 9.92 degrees laterally to 3.44 degrees medially. The final position of this tooth in this dimension was with 5.50 degrees of tip laterally. Very small moments were produced around the x-axis while moments around the y-axis ranged from -851g-mm to -55g-mm.

The overall rate of tooth movement in an antero-posterior direction for tooth #23 in patient D.R. was 0.72 millimeters per 28 days. The rate for each phase of tooth movement can be found in Table 4.5.

Table 4.6 summarizes the positions of each cuspid after the first measured movement (ie. day one to day 3) as well as the final position of each cuspid in relation to its original position. The next chapter will discuss these various positions.

TABLE 4.5: RATES OF TOOTH MOVEMENT ANTERO-POSTERIORLY.

	B.J.#23	B.J.#13	J.B.#23	D.R.#23
PHASE 1	day 1-4 0.41/3 or	day 1-8 1.07/7 or	day 1-3 0.61/2 or	day 1-3 0.21/2 or
millimeters per day	=0.136	=0.153	=0.305	=0.105
PHASE II	day 4-15 $\frac{0.51-0.41}{11}$	day 8-52 $\frac{.87-1.07}{44}$	day 3-15 $\frac{0.58-0.61}{12}$	day 3-15 $\frac{0.25-0.21}{12}$
millimeters per day	= 0.00909	=-0.0045	=0.0025	=0.00333
PHASE III	day 15-59 $\frac{1.2-0.51}{44}$	day52-59 $\frac{1.42-.87}{7}$	day 15-29 $\frac{1.03-.58}{14}$	day 15-50 $\frac{1.28-0.25}{35}$
millimeters per day	=0.01568	=0.07857	=0.03214	=0.02943
OVERALL	$\frac{1.2}{59} \times 28$	$\frac{1.42}{59} \times 28$	$\frac{1.03}{29} \times 28$	$\frac{1.28}{50} \times 28$
millimeters per 28days	= 0.5695	= 0.6739	= 0.9945	= 0.7168

TABLE 4.6: SUMMARY OF INITIAL MOVEMENT AND FINAL TOOTH POSITIONS.

		BJ #23	BJ#13	JB#23	DR#23
FIRST MOVEMENT (measurement taken from first return visit after activation and compared to initial position)	AP	posterior	posterior	posterior	posterior
	ML	lateral	medial	lateral	medial
	OG	gingival	occlusal	occlusal	occlusal
	CROWN AP	posterior	posterior	posterior	posterior
	CROWN ML	lateral	medial	medial	lateral
	CROWN PL\PM	post-med	post-med	post-med	post-lat
LAST MOVEMENT					
(final tooth position at end of activation period when compared to initial tooth position)	AP	posterior	posterior	posterior	posterior
	ML	lateral	lateral	lateral	lateral
	OG	gingival	gingival	gingival	occlusal
	CROWN AP	anterior	posterior	posterior	anterior
	CROWN ML	lateral	lateral	lateral	lateral
	CROWN PL\PM	post-med	post-med	post-med	post-med

LEGEND

AP = antero-posterior
ML = medio-lateral
OG = occluso-gingival
CROWN AP = crown tipping anterior-posterior around the z-axis
CROWN ML = crown tipping medio-lateral around the x-axis (torque)
CROWN PL\PM = crown rotating around the y-axis

5. DISCUSSION

5.1 INTRODUCTION

The primary goal of this study was to determine the rate of tooth movement in response to a known applied force system. It was hoped that the design of this study would bring the orthodontic community closer to defining the magnitude of force required to produce the optimum rate of tooth movement. While a study based on such a limited sample size does not readily lend itself to drawing final conclusions, many valuable observations were made.

The final analysis of this study is based on the retraction of four cuspids in three patients over periods of four to eight weeks. As mentioned in the methods and materials section, data was collected from a total of seven cuspids in four patients. Reasons for the exclusion of the data collected from three cuspids will be presented in this chapter.

The discussion of the data is divided into sections relating to each dimension of tooth movement. Thus for any given direction of movement all four cuspids will be discussed. Discussion of the data in this manner allows one to more readily detect trends. The description for each type of tooth movement examines the position of the tooth relative to its original position. The corresponding forces and moments for each type of tooth movement will be incorporated into each of these sections.

Finally, the rate of tooth movement will be discussed separately.

5.2 STABILITY OF THE REFERENCE POINTS

For the measurement of tooth movement to have any significance, ensuring the stability of the reference points or areas was critical. For this project three references were chosen: the anchor segments on each side of the dental arch along with one palatal rugae.

As described in the Methods and Materials chapter, anchor segments were established to produce as little tooth movement in these areas as possible. The stability of these segments was verified in two different ways. First, each patient's individualized orientation splint was utilized on all casts within that patient's set. In each case the splint accurately fit each sequential cast from start to finish. An accurate fit such as this suggests that the anchor segments on each side of the arch remained stable with respect to each other and that the teeth within each segment remained in constant relationship with each other. To further verify the stability of the anchor segments, measurements of selected points within the anchor segments were made with respect to the axis system. Comparisons of these measurements for each subsequent cast were made. Consistency in the measurement of these points within a standard range of error (+\- 0.2mm) was an indication of the stablility of these points. In each case the stability of the anchor segments was verified.

Once the stability of the anchor segments was verified, stability of the rugae could easily be checked. To do this, the distance from the rugae to a given point on the anchor segment was compared for each cast. For each set of casts, the rugae was observed to be stable.

Verification of the stability of the reference points ensured that the description of the relative movement of the cuspids was accurate within the parameters of this study.

5.3 ACCURACY OF THE FORCE SYSTEM MEASUREMENTS

As previously mentioned, the force system measuring apparatus was capable of measuring to a maximum of 1,000 grams (g) and 20,000 gram-millimeters (g-mm) with an error of +\- 3% of full scale. The maximum forces and moments used in this study were approximately 25% and 10% respectively of full measurable range on the machine. As the forces and moments decrease, the likelihood of machine error becomes greater. This error helps to explain some of the unusual patterns of forces and moments reported in the results at low force and moment levels.

In an attempt to minimze the machine measurement error, each loop was tested four times to ensure consistency in the measurements. The moments and forces measured in each of the four activations for each loop were virtually identical.

5.4 ANTERIOR AND POSTERIOR MOVEMENT

The net tooth movement antero-posteriorly (AP) in all four patients was predictably posterior. The range of posterior movement over a 28 day period was from 0.57 millimeters (mm) in patient BJ#23 to 0.99mm in patient JB.

In each case, AP movement tended to occur in three phases. These phases shall be described as phases I, II, and III. These phases were subjectively chosen to closely resemble the phases described in the literature as the initial, the lag and the post-lag phases (Reitan, 1975).

During phase I, the cupsid rapidly moved posteriorly (See Results, Table 4.5). The observed rates of tooth movement during this phase ranged from 0.105mm\day (DR) to 0.305mm\day (JB). In each case, the force level (Px) decreased significantly. The initial and final force levels along with the rate of tooth movement for this phase are summarized in Table 5.1.

An initial rapid movement of the cuspid posteriorly was expected. This movement corresponds to the compression of the periodontal membrane space in response to a force in that direction. The resultant tooth movement naturally caused the force level to decrease.

During Phase II, very little tooth movement in an AP direction was observed. This phase appeared to last between eleven and twelve days for three of the four cuspids. In patient BJ#13, this phase lasted considerably longer (44 days). This phase was the most difficult

Table 5.1: Initial and final force levels (AP) and rate of tooth movements for phase I.

	BJ#23	BJ#13	JB	DR
Initial force (g)	278	215	228	285
Final force (g)	188	145	171	225
Rate of tooth movement. (mm\day)	0.136	0.153	0.305	0.105

Table 5.2: Initial and final force levels (AP) and rate of tooth movements for phase II.

	BJ#23	BJ#13	JB	DR
Initial force (g)	188	145	171	225
Final force (g)	188	65	157	181
Rate of tooth movement. (mm\day)	0.0090	-0.0045	0.0025	0.0033

Table 5.3: Initial and final force levels (AP) and rate of tooth movements for phase III.

	BJ#23	BJ#13	JB	DR
Initial force (g)	188	65	157	181
Final force (g)	106	65	105	28
Rate of tooth movement. (mm\day)	0.0152	0.0786	0.0321	0.0294
(mm\28 days)	0.439	2.20	0.898	0.823

phase to distinguish for this cuspid because of the erratic nature of its movement AP.

The corresponding force levels along with the rate of tooth movement for this period are outlined in Table 5.2.

Despite the relative lack of tooth movement in an AP direction, the force levels in all but one case dropped significantly. The decay in the force system may possibly be accounted for by changes in tooth position in other dimensions. For example, depending on the position of the reference point with respect to the tooth, a rotation in the postero-medial direction simultaneously with a posterior movement might be measured as a lack of posterior tooth movement. This can be seen to be the case in patient BJ#13 and JB. Similarly, a posterior movement simultaneously with an uprighting or anterior crown tip could be interpreted as a lack of posterior movement of the tooth. This movement in an AP direction does not necessarily preclude a change in the force level. Another possible explanation for the apparent lack of tooth movement despite a decrease in the force system may be a result of the stretching of the tie-back ligatures. Under the influence of mastication and daily function , it is possible that these ligatures were stretched and therefore allowed some deactivation of the appliances. The stretching of the ligatures most likely accounts for the amount of measured posterior tooth movement being less than the measured amount of activation of the appliances.

During phase III each of the four cuspids experienced a net posterior movement. The rate of tooth movement ranged from 0.015mm\day (BJ#23) to 0.078mm\day (BJ#13). The corresponding initial and final force values for this phase along with the rate of tooth movement for this phase are presented in Table 5.3.

An interesting observation made primarily during phase III was that each cuspid appeared to move anteriorly on several occasions. A number of possible explanations can account for this movement.

As noted in the previous chapter, on several occasions loose ligatures were observed in two patients: in BJ#23 on day 32; in BJ#13 on day 35; and in DR on days 13 and 27. In all but one instance (DR day 13) the cuspid appeared to move anteriorly in response to the loose ligature. For patient BJ#23 the cuspid began to move anteriorly on day 18. It is possible that the ligature had loosened as early as day 18 but had not been noticed until day 32. Anterior movement of the cuspid resulting from loose ligatures ranged from 0.23mm (DR day 27) to 0.46mm (BJ#13 day 35).

The observed anterior tooth movement may also be explained, in some cases, by other simultaneous tooth movements such as rotations and tipping. Similar to the explanation provided for an apparent lack of tooth movement during phase II the cuspids may have appeared to move anteriorly if the amount of rotation or anterior tipping exceeded the amount of posterior movement. It is conceivable that a rotation of this nature occurred for patient BJ#23 on day 46. A tipping movement of this nature may account for the effective anterior movement of the cuspid in patient DR on day 36.

Since not all the apparent anterior movements of the cuspids can be explained by either of these two theories, other possible explanations must be considered. One explanation may be that the rigidity of the impression material may have been stiff enough to actually create some tooth movement within the already weakened periodontal ligament. Thus, as the impression material was seated, the tooth may have been compressed against the non-resorptive side of the tooth's socket since it could not be pushed any further posteriorly. While this explanation may be used to partially explain some of the anterior movement observed, it neglects to explain why an apparent anterior movement of the cuspid is not consistently seen in the other phases of tooth movement.

Another possible explanation for the apparent anterior movement of the cuspids during phase III could simply be accounted for by measurement errors. As previously mentioned, the measurement error was +\- 0.2mm. In most instances, the deviations in movement anteriorly are within this range. However, similar to the explanation based on the impression material, the results based on this theory are not consistent in each phase. It is possible that measurement errors in more than one dimension have been compounded so that when the angular measurements were made, larger errors were produced. If this were true, it is conceivable that each anterior movement could be accounted for by a compensating rotation or tip.

The only other possible explanation that could account for the apparent anterior movement of the cupsids is that the cuspids actually did move anteriorly. Knowing that a posterior force was present throughout the activation period makes this explanation unattractive. It is possible, however, that the tooth could have moved anteriorly within the periodontal ligament space as a result of tension provided by the transeptal fibers joining the lateral incisors to the cuspids. The anterior force provided by these fibers may have overcome the weakening posterior force of the retraction loop.

The overall rates of tooth movement AP for these four cuspids ranged from 0.57mm\28days (BJ#23) to 0.99mm\28days (See Results Table 4.5). Within this force range, no conclusions can be made relating the overall rate or velocity of tooth movement to force levels since the tooth with the greatest force level (DR) moved approximately the same amount AP as the tooth with the smallest force level (BJ#13). The tooth with the greatest amount of tooth movement (JB) had a force level slightly larger than the tooth with the lowest force level (BJ#13).

5.5 MEDIAL AND LATERAL MOVEMENT

As expected, each cuspid had a final position which was lateral to its original position. Lateral movement at the end of the activation period ranged from 0.60mm

(BJ#23) to 1.42mm (DR).

Movement of the cuspid laterally would naturally be anticipated since the cuspid moves from a narrower to a wider part of the arch. The amount of lateral movement primarily depends on two factors:

1. the relative position medio-laterally of the cuspid with respect to the anchor segment, measured in the transverse plane prior to activation of the appliance; and
2. the presence or absence of a force in the transverse plane (z-axis) either directly as a result of a compensatory bend or as a result of the nature of the appliance.

The relative amounts of medio-lateral (ML) tooth movements along with the maximum transverse force levels are presented in Table 5.4. The transverse force levels were deliberately kept to a minimum by compensating bends placed in the anterior portion of the appliances when necessary. These bends were placed to ensure that the appliances were clinically passive prior to the initial activation.

It is apparent that no correlation can be seen between the magnitude of force transversely and the amount of tooth movement laterally. It can therefore be assumed that the amount of tooth movement laterally can be primarily accounted for by the relative change in position of the cuspid medio-laterally with respect to the anchor segment.

Similar to what was observed with the AP movement,

Table 5.4: The final medio-lateral tooth position and the corresponding transverse force levels.

	BJ#23	BJ#13	JB	DR
Lateral Tooth position (mm)	0.63	1.08	1.30	1.42
Maximum transverse force (g)	27	38	19	35

Table 5.5: Final occluso-gingival tooth position and maximum vertical force levels.

	BJ#23	BJ#13	JB	DR
Final tooth position (mm)*	-0.33	-0.18	-0.19	0.22
Maximum vertical force (Py) (g)**	-56	-99	-50	-25

* positive = occlusal

** all vertical forces presented are gingival the ML movement did not occur solely in a lateral direction. At several periods in time, each cuspid did display some movement medially. While the medial movement was minimal in patient JB it was quite pronounced in both cuspids in patient BJ. Again, a postero-medial rotation greater than the lateral movement of the tooth may explain the apparent behavior of the teeth at several points in time ie. BJ#23 days 43 to 49. In patient BJ the medial movement of the the left cuspid seen from days 22 to 32 was likely a result of the aforementioned loose ligature.

Other possible explanations to account for the apparent medial movement of the tooth include:

1. increased medial crown tip greater than the lateral movement;

2. compression of the periodontal ligament during the impression procedure;

3. the compounding effect of measurement errors in more than one dimension; and

4. an actual medial movement as a result of tension in the transeptal fibers.

Whatever the explanation may be that accounts for the sporadic medial movements, in each case the final position of the cupsid was distinctly lateral to its initial position. This final position was achieved with a minimal amount of force in this direction. It may also be noted that the rate of tooth movement laterally tended to be more or less proportional to the rate of tooth movement posteriorly.

5.6 OCCLUSAL AND GINGIVAL MOVEMENTS

The cuspids in each patient exhibited very little change occluso-gingivally at the end of the activation period. The range was from 0.33mm gingivally (BJ#23) to 0.22mm occlusally (DR). Table 5.5 summarizes the corresponding forces in the vertical dimension (Py) along with the final tooth positions occluso-gingivally. Despite the fact that the force levels were minimal to moderate in the gingival direction, the change in tooth position occluso-gingivally remained rather small.

The vertical movement of all four cuspids showed some alternation between occlusal and gingival movement. Although the range of movement was kept quite low, there appeared to be no trend towards either a net occlusal or gingival movement. It is possible that natural occlusal forces had an effect on the transient tooth positions.

The fluctuation between the occlusal and the gingival positions of the cuspids may also be explained by a corresponding tipping or uprighting of the tooth. An example of this type of movement can be seen in patient BJ, tooth #13 day 46.

It is apparent that despite relatively large gingival forces such as produced by the appliance seen on BJ#13 (-99g), it seems that the stiffness of the appliance was able to prevent a large gingival movement of the cuspid. In fact, had the activation period been decreased by seven days, the final tooth position for BJ#13 would have been in the occlusal direction.

5.7 ANTERIOR AND POSTERIOR CROWN TIPPING

The initial movement in this direction of the four cuspids was a tip of the crown posteriorly. With a force in the posterior direction away from the center of resistance, this movement would be expected.

Throughout the activation period each tooth studied underwent a series of tipping and uprighting movements. The maximum anterior and posterior tipping movements were 11.95 (BJ#23) and 16.40 (BJ#13) degrees respectively. The range of anterior and posterior tipping values along with the maximum and minimum moment values around the z-axis are presented in Table 5.6.

The data reveals that although these teeth appeared clinically to be moving bodily, they were in fact alternating between tipping and uprighting movements within a small range of motion. For each cuspid, the moments generated by the appliances tended to favour tipping in the posterior direction. Despite this fact, a minimal amount of posterior tipping was observed.

The average moment-to-force ratios (M\F) in millimeters for each aplliance is: BJ#23 = -3.8mm; BJ#13 = -4.75mm; JB = -3.8mm; DR = -4.0mm. These ratios represent the net effect of the counter moments introduced by the appliance plus the moment generated by the force (Px) applied at the bracket being resisted at the centre of resistance of the tooth. In each case, the given M\F ratio would suggest that the tooth would have a tendency

Table 5.6: Range of tipping values and moments around the z-axis.

	BJ#23	BJ#13	JB	DR
Maximum posterior tip (degrees)	1.47	16.40	7.36	13.41
Maximum anterior tip (degrees)	11.95	3.79	4.92	9.37
Maximum moment around z-axis (g-mm)	-1,013	-951	-890	-1,089
Minimum moment around z-axis (g-mm)	-403	-230	-170	-117

Table 5.7: Range of tipping values and moments around the x-axis.

	BJ#23	BJ#13	JB	DR
Maximum medial tip (degrees)	8.13	15.26	14.73	9.92
Maximum lateral tip (degrees)	10.44	3.61	3.02	3.44
Maximum moment around x-axis (-ve = medial;g-mm)	-232	-126	84	168

to tip distally. As is evident from Table 5.6, AP tipping ranged from small amounts anteriorly to small amounts posteriorly. In fact, in two cases the final tooth position was one in which the crown had been tipped anteriorly with respect to its initial position (BJ#23 and DR). Thus it is apparent that the loop was able to partially counteract the tendency towards tipping posteriorly. This result was accomplished without any compensating gable bends.

It is also interesting to note that retying of the loose ligatures in patients BJ and DR did not significantly alter the antero-posterior crown tip.

5.8 MEDIAL AND LATERAL TIPPING MOVEMENT

Medial and lateral crown tipping measurements were made by calculating the differences between the most incisal and most gingival points with repsect to the transverse plane over time. Effects of postero-lateral or postero-meidal rotations on this measurement were found to be insignificant in a previous study by Duff (1987).

In two cases (BJ#13 and JB), the initial movement of the cuspid was a medial crown tip. Fluctuations between medial and lateral crown tipping were noticed in each case with a greater tendency towards lateral crown tipping seen in JB and DR and a greater tendency toward medial tipping seen in BJ. Table 5.7 summarizes the maximum and minimum medio-lateral tipping movements along with the corresponding maximum moments around the x-axis. It is interesting to note that the moment around the x-axis was negative in both cuspids of BJ. This moment corresponds with the stronger tendency towards medial movement seen in these two cuspids. Likewise, the moment around this axis was positive in the cases of JB abd DR indicating a tendency towards lateral crown tipping.

The moments measured around this axis were noticably very small and below the 3% accuracy range.

In patient BJ#23 it is interesting to note the effect of the loose ligature on the medial-lateral tip of the crown. The maximum amount of lateral crown tip had been observed just prior to the suspected initial loosening of the ligature. On day 32 when the loose ligature was first noticed and retied, close to the maximum amount of medial crown tip for this cuspid was observed. The same trend was not detected when the ligature was noticed to be loose in the opposite cuspid in patient BJ and in patient DR. Perhaps medial movement of these cuspids was avoided by a more immediate observation of the loose ligatures. The movement from lateral to medial tipping seen in patient BJ#23 indicates that either a greater positive moment was present around the x-axis during that period of time or that there was a greater occlusally directed force present.

In all cases the final tip position of the cuspids was lateral to its original position. This final position of the cuspids may be a result of the combined effect of a lateral and a gingival force exerted on the teeth.

5.9 POSTERO-LATERAL AND POSTERO-MEDIAL ROTATION

Of the four cuspids retracted only one cuspid did not experience an initial postero-medial rotation (DR). However, all four cuspids had a postero-medial rotation at the end of the activation period when compared to their original positions. Although there was some fluctuation between postero-lateral and postero-medial rotation, postero-medial rotation was predominant. Some rotation postero-medially would be the expected and desired tooth movement as the tooth moved into a wider part of the dental arch. The range of postero-medial and postero-lateral rotations along with the corresponding maximum and minimum moments around the y-axis are presented in Table 5.8.

The appliance attached to each cuspid can be seen to have produced a moment around the y-axis that favoured a postero-medial rotation. Despite this tendency towards postero-medial rotation, two of the cuspids (BJ#13 and DR) actually experienced postero-lateral rotations several times during the activation period. In patient DR, two of the times the postero-lateral rotations were observed corresponded with days in which the ligature ties were observed to be loose. The initial trend toward postero-lateral rotation observed in this patient was likely due to the fact that this tooth was positioned disto-lingually with respect to the anchor segments. In patient BJ#13, possible explanations for this rotation

Table 5.8: Range of rotation and moment values around the y-axis.

	BJ#23	BJ#13	JB	DR
Maximum postero-medial rotation (degrees)	25.48	8.50	18.80	9.48
Maximum postero-lateral rotation (degrees)	-	6.79	0.49	5.61
Maximum moment around y-axis (-ve=post-med; g-mm)	-1,577	-689	-767	-851
Minimum moment around y-axis (My; g-mm)	-768	-226	-120	-55

might include compounding measurement errors and\or tension of the transseptal fibers. In all cases, the maximum postero-medial rotation was significantly greater than the maximum postero-lateral rotation.

The fact that two of the cuspids were observed to rotate postero-laterally at all when significant moments were applied in the opposite direction requires some attention. It is apparent that the stiffness of the loop in the transverse plane prevented the tooth from rotating completely postero-medially. It is also possible that the tension generated by the transseptal fibers was great enough to counteract the postero-medial rotation.

In patient BJ tooth #23, a postero-lateral rotation was not observed during the activation period. In fact, this cuspid exhibited the largest degree of postero-medial rotation of all four cuspids. It is not surprising to note that the activation loop used in this cuspid had a moment around the y-axis almost two times greater than the moments around the same axis produced by the other appliances. The explanation for this finding stems from the fact that this appliance required a much greater compensating bend in the medial direction in order to achieve passive engagement in the cuspid bracket prior to activation. This bend was necessary for this tooth because of the difference in relative distances in the transverse plane between the anchor segment and the cuspid. Without this compensating bend, a much greater transverse force would have been present. In light of the initial position of this cuspid, a postero-medial rotation was a desirable movement because the cuspid had to move from a more anterior part of the dental arch to a more posterior position.

5.10 THE RATE OF TOOTH MOVEMENT

The following observations regarding the rate of tooth movement have been based strictly on the small sample size of this study. Because this sample size is not statistically significant, broad, universal conclusions cannot be made. However, many interesting observations were made, some of which may serve as a future basis for further research.

Figure 5.1 represents the average rates of antero-posterior tooth movements plotted against the mean posterior force levels for each cuspid during Phase I. A line representing the best fit of these points has been calculated. Similar plots representing Phase II and Phase III can be seen in Figures 5.2 and 5.3 respectively.

Figure 5.1 illustrates that there was a negative relationship between force and velocity for Phase I. In other words, an increase in force within this range during this phase caused a decrease in the velocity of tooth movement. This plot indicates that the relationship between force and velocity (the slope of the line) was -0.00046 mm\day\g. The best fit straight line has been calculated to exclude patient JB since this point is quite out of line with the others. Two possible explanations

FIGURE 5.1: VELOCITY OF TOOTH MOVEMENT PLOTTED AGAINST POSTERIOR FORCE DURING PHASE I.

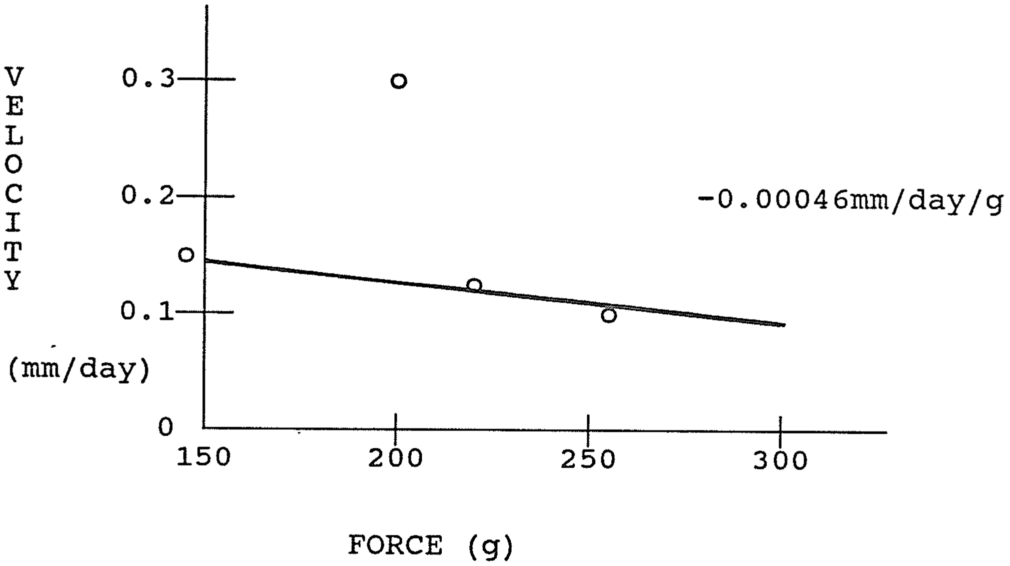


FIGURE 5.2: VELOCITY OF TOOTH MOVEMENT PLOTTED AGAINST POSTERIOR FORCE DURING PHASE II.

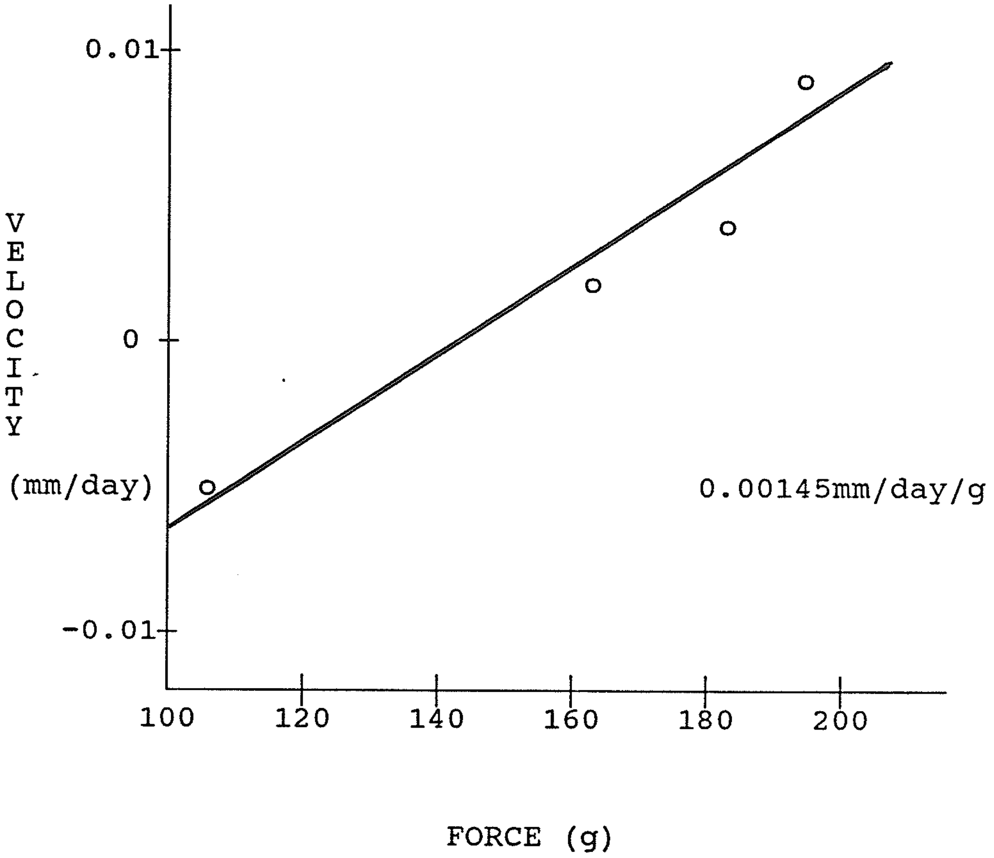
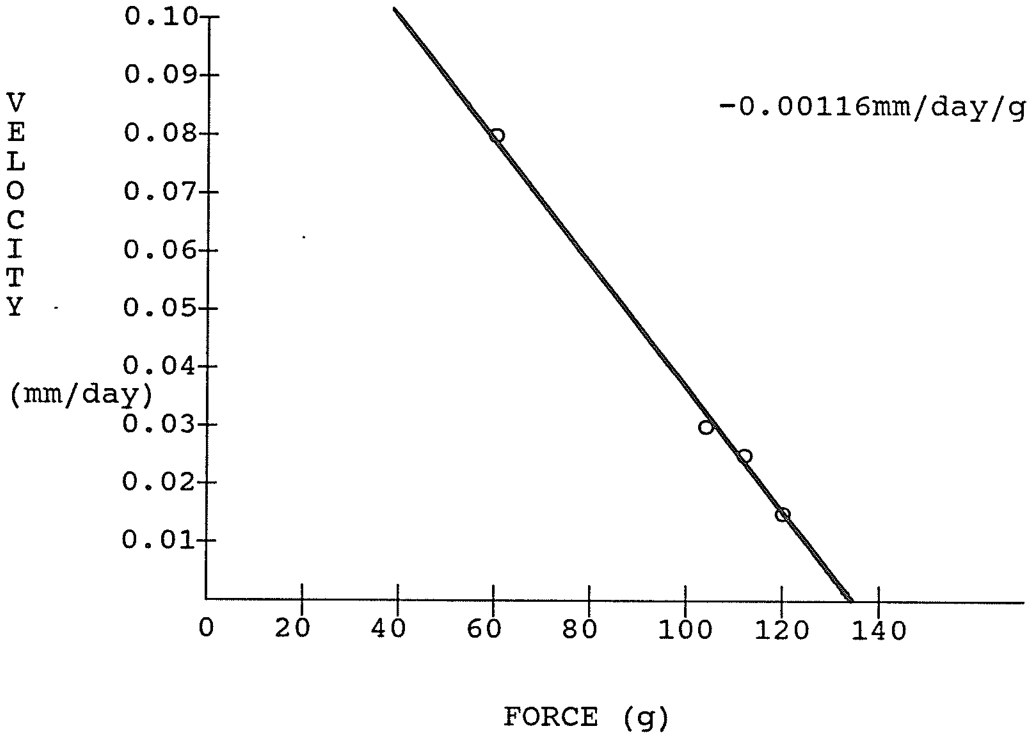


FIGURE 5.3: VELOCITY OF TOOTH MOVEMENT PLOTTED AGAINST POSTERIOR FORCE DURING PHASE III.



can account for the variation of this cuspid. Firstly, it is possible that with a measurement error of +\- 0.2mm that the initial movement was somewhat smaller than what was actually measured. If this were true, the rate of tooth movement over this time period would be reduced. Secondly, if patient JB returned 3 days after the first activation as patient BJ did rather than 2 days after, the rate of tooth movement for this phase would have been reduced to 0.203mm\day. A combination of both of these factors would certainly have the effect of decreasing the calculated velocity of the tooth significantly. Thus the difference in the measurement time interval in this phase is most likely responsible for the aberrant point.

The relationship between the mean posterior force and velocity during phase II can be seen in Figure 2. Again a best fitting line was constructed for these points. This plot illustrates that a positive relationship existed between the rate of tooth movement and the mean applied posterior force. Alternatively stated, a greater posterior force during this time period caused a greater amount of tooth movement per time. The relationship between force and velocity (the slope) for this phase was 0.000145mm\day\g.

During Phase III, a negative relationship existed between the velocity of tooth movement and the mean posterior force. A best fitting line indicates that the relationship between velocity and force for this phase was -0.00116mm\day\g - 2.5 times greater than that of Phase I.

For all three phases, the correlation coefficient (r) was greater that 0.9.

Although the results from this study are based on a small sample size, they clearly demonstrate a interesting finding. It is apparant that the relationship between the force levels and the velocity of tooth movement varies considerably for each phase of tooth movement. This observation may have a definite impact on the manner in which the concept of an optimal force has been approached. Perhaps the lack of agreement amongst various researchers as to what "the" optimal force is for a specific type of tooth movement is largely because there is not one optimal force level but likely three - one for each phase of tooth movement. Because this study only examined the rate of tooth movement over the initial activation period, it is uncertain whether or not this same pattern exists during subsequent activation periods. Additionally an examination of the biological response to the various force levels would be necessary before the final verdict regarding optimum force levels can be made.

5.11 EXCLUSION OF COLLECTED DATA (PATIENT RZ AND JB#13)

As previously mentioned, data was collected and analyzed for a total of seven cuspids. The results for patient JB#13 were omitted becasue of an almost complete lack of movement of the tooth. Some movement in all directions was observed over the 43 day period but the final position of this cuspid was virtually the same as the initial position.

On day 29 the author decided to remove the loop to test whether or not it had deformed. No deformation in the loop was observed so it was reactivated. Upon reactivation the ligature was securely tightened to eliminate the possibility of this being the problem.

Initially it was postulated that perhaps the tooth had ankylosed. This theory was subsequently ruled out since this cupsid was eventually retracted under continued orthodontic treatment. No additional theories have been found to explain the temporary lack of tooth movement of this cuspid. Fortunately the aberrant behavior exhibited by this tooth is not normally observed in clinical situations.

The results for patient RZ were omitted from this study because of a technical problem that interferred with the accurate collection of the data. To ensure that the appliances were not disturbed during the impression procedure, each appliance along with the brackets and bands were blocked out with wax immediately prior to the insertion of the impression material. The cuspids in patient RZ were of a shape that permitted the tooth templates to swivel when they were seated. As a result, because there was no positive seating area such as a bracket with which to lock the tooth templates in place, reference points were inconsistently placed on the cuspids of subsequent casts. The lack of consistency in the placement of the reference points on the cuspids made the collected data meaningless.

5.12 SUMMARY OF DISCUSSION

A study based on a small sample size such as this makes it inappropriate to draw definite conclusions. This study does, however, illustrate some interesting findings.

Table 4.6 (Results Chapter) summarizes the initial movement and final tooth positions. It is apparent that the desired linear movements of the tooth posteriorly and laterally along with the desired postero-medial rotation were achieved. These movements were achieved with minimal changes in the occluso-gingival direction as well as with minimal amounts of tipping of the crown both antero-posteriorly and medio-laterally. However, a series of antero-posterior tipping and uprighting movements occurred as the tooth moved posteriorly. Control of tooth movement was therefore achieved not primarily because of compensatory moment-to-force ratios but because of the relative stiffness of the appliance in the dimensions of unwanted tooth movement. This observation supports the work done by Duff (1987). Additionally the desired tooth movements occurred without any measured loss of anchorage during the initial activation period. The data does not permit conclusions about anchorage stability during the reactivation process.

Finally, an attempt was made to determine if a relationship between the rate of tooth movement and the given force system existed. The data collected from this study clearly indicated that a definite relationship existed between the velocity of tooth movement and the applied force for each phase of tooth movement.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The purpose of this study was to examine the rate of tooth movement in response to a known applied force system. It was hoped that the examination of this relationship would allow for some insight into the concept of an optimal force. Based on the analysis of the limited data collected in this study, the following conclusions can be drawn.

1. There is likely not one optimal force level for any particular type of tooth movement. Instead, there is evidence to suggest that the optimal force level differs for each phase of tooth movement.

2. Analysis of the movements of the cuspids monitored in this study reveals:

   a. Tooth movement in any one direction does not occur in a straight path. Instead, movement tends to follow a jiggling process.

   b. Tooth movement occurs in the directions that may be anticipated from an analysis of the force system applied without any clinically unacceptable movement.

   c. The stiffness of the appliance in the directions in which tooth movement is not wanted inhibits unwanted tooth movement.

3. Establishing stable anchor segments which could be used to monitor tooth movement of the cuspid is possible. Likewise, a chosen point on the palatal rugae can act as a

stable reference over short periods of time.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

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

1. The adaptation of a positive seat on the palatal side of the cuspids being retracted to ensure proper adaptation of the tooth template. A bonded lingual attachment placed prior to the activation period would help to eliminate any swivel of the tooth template while marking reference points on each cast. This procedure would ensure a more accurate placement of reference points on the cuspid teeth when the anatomy of the tooth would render this procedure difficult.

2. The incorporation of a wider range of initial force levels on a larger sample of patients so that a better understanding between the force-velocity relationship can be gained.

3. The day-to-day observation of tooth movement over more than just the initial activation period. Data collected from subsequent activation periods may reveal differences in overall rates of tooth movement.

4. The study of identical pre-calibrated force levels on different patients of different ages and sexes so that inter-patient variation can be identified.

5. The correlation of subsequent studies that reveal a clearer relationship between rate of tooth movement and applied force systems to studies examining the biological effects of forces applied to teeth. A study such as this may truly be able to define optimal force levels or

ranges.

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APPENDIX A

The measuring apparatus used in this study is basically the same apparatus as that used in the studies of Duff (1987) and Sonya (1987). The essential components of the machine are:

a) A measuring system.

b) A data acquisition system.

c) A minicomputer.

As in the study done by Duff and Sonya, these instruments were linked to an IBM computer with multiple display functions. Figure A.1 shows the set-up of the above apparatus.

THE MEASURING SYSTEM

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

There are four major parts to the instrument: the frame, an internal suspended ring, a triangular block, and an electromagnetic vibrator. See Figure A.2. Two types of transducers are used on the measuring machine. Type A tranducers measure horizontal forces and the pivoting moment. Type B transducers are attached to the frame and to the suspended ring, and measure vertical forces and tipping moments.

The measuring instrument has a maximum force range of 1000 grams and a maximum moment range of 20,000 gram millimetres. The machine has a total error range of +\- 3% of maximum force and moment values.

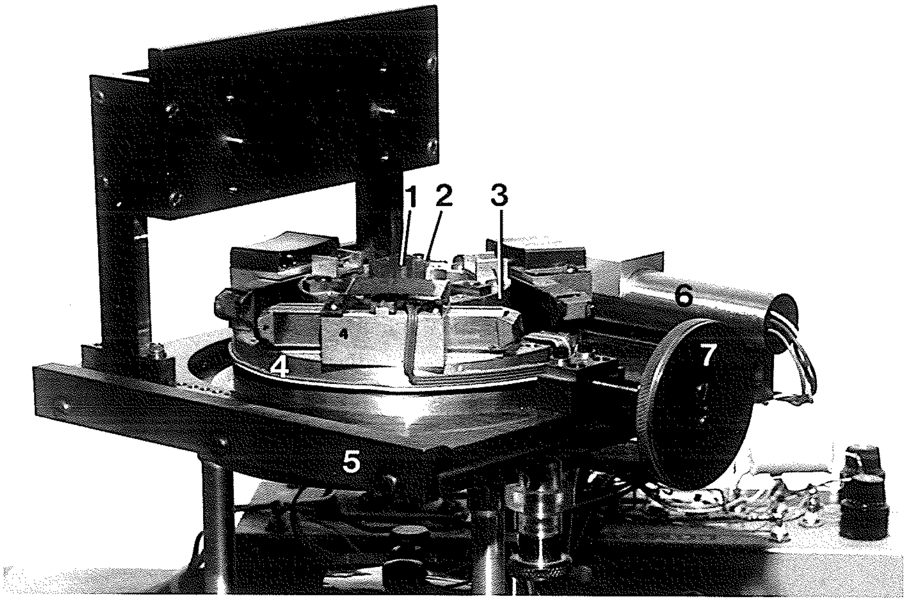
The Data Acquisition System and Minicomputer are those described by Lack (1980).

COMPUTER PROGRAMS:

Modified programs were written for the study by Duff and Sonya by McLachlan. They consisted of a data acquisition program and a data analysis program. In addition a data transfer program was written, which allowed collected data to be directly transferred to the IBM personal computer for storage and analysis. With these programs it was possible to change the effective centre of resistance of a measured tooth for a specific loop. Changes in the nature of the force system could then be assessed.

1. Measuring apparatus.
2. Hewlett-Packard minicomputer.
3. Data Acquisition System.
4. IBM minicomputer.

Figure A.1 General view of measuring instrumentation.



1. Center of measuring machine.
2. Triangular block.
3. Internal ring with Type A transducers.
4. External ring with Type B transducers.
5. Frame.
6. Linear voltage displacement transducer.
7. Adjustment screw.

Figure A.2 Detailed view of measuring instrumentation.