THE UNIVERSITY OF MANITOBA

ORTHODONTIC TOOTH MOVEMENT IN RESPONSE TO KNOWN FORCE SYSTEMS: MOLAR UPRIGHTING

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BY

DOROTHY A. SONYA

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DOROTHY ANNE SONYA

A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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ABSTRACT

The orthodontic literature has frequently addressed the relationship of tooth movement to applied forces and moments. However, there still remains a great variability in the magnitudes of applied forces considered desirable for specific tooth movements. One of the most significant reasons for the variability in "desired" forces is that most of this information has been gained from two-dimensional studies attempting to quantify a three-dimensional force system.

The present investigation was aimed at developing a technique for three-dimensional measurement of tooth movement, as a result of known applied force systems also measured in three dimensions.

For this study, the mechanically determinate system of molar uprighting was chosen because it is a relatively large tooth movement. Thus, measurement errors due to tooth mobility and measurement procedures would be small relative to the tooth movement. A similar investigation using cuspid retraction is currently being undertaken (Duff, 1987).

A machine capable of measuring *in vitro* forces and moments in three dimensions simultaneously (Paquien, 1978)

was modified so that appliances could be measured in vitro under geometric conditions similar to those found in the clinical situation. To transfer the clinical situation to the laboratory, a technique was developed using study casts .op and duplicate loops.

Results obtained from this investigation suggested:

(1) The technique developed in this investigation permitted satisfactory measurement of tooth movement and of the applied force systems.

(2) In all cases, the primary objective of molar uprighting was achieved.

(3) The molars of one male and two female patients of various ages having different magnitudes of applied uprighting moments were used in this investigation. The rate of uprighting was found to be similar in all cases regardless of age, sex or magnitude of measured uprighting moment. This lack of variation might be due to the fact that the high stress/unit area generated in molar uprighting was such that even the lowest applied moment exceeded the optimum moment for uprighting. Any increase in applied moments above this value might not produce any differences in the rate of tooth movement (Quinn and Yoshikawa, 1985). However, effects of age and/or sex cannot be

discounted by these results.

(4) Spurious tooth movements (tooth movements in directions other than the uprighting movement) were small and may have been relatd to the type of uprighting loop used.

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To my husband, Murray,

and

to my parents.

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CHAPTER I

INTRODUCTION

INTRODUCTION

The response of the tooth, periodontal ligament and alveolar bone to force systems applied to the tooth during orthodontic mechanotherapy is still uncertain. Therefore, the "ideal" force levels required to produce the greatest amount of desired tooth movement in the shortest time, with the least amount of biological damage, undesired tooth movement and patient discomfort, also remain unknown. This serious gap in our knowledge, to a great extent, reflects the extreme difficulty in providing accurate quantitative information concerning both the force systems and the resulting tooth movements.

A review of the orthodontic literature reveals conflicting conclusions regarding the magnitudes of forces required to produce certain tooth movements. These reported force ranges vary greatly, from 25 grams/mm^2 up to 1,515 grams.

One major reason for the large range of stipulated forces for various tooth movements is that, in many experiments, two-dimensional data are gathered and analyzed in an attempt to describe a three-dimensional phenomena. A second reason for the variability of prescribed forces for tooth movement results from the mechanical complexity of the arch wire-bracket-tooth system. This mechanical complexity includes factors such as friction due to ligation, remoteness of the centre of resistance from the point of force application, intra-arch constraints and the difficulty in calibration of applied forces and moments generated by appliance activation. A third factor that could contribute to lack of precision in our force-tooth movement knowledge is biological variability. In summary then, very little is known about tooth movement in response to an accurately determined three-dimensional force system.

In order to begin to determine the best force and moment for a given tooth movement, namely tipping, molar uprighting was chosen. Molar uprighting is a frequently encountered clinical problem requiring relatively large tooth movements which would reduce the impact of irreducible measurement errors. Also, molar uprighting can be accomplished by a mechanically determinate "two-tooth" system.

Three-dimensional mechanical analysis of molar uprighting required the development of several techniques:

I. A technique for longitudinal three-dimensional, in vitro analysis of in vivo tooth movement. Measuring tooth movement accurately intraorally is very difficult because of lack of space and the difficulty in locating, checking and measuring stable landmarks. However, accurate study casts might enable visual as well as mathematical calculations to be made.

II. A technique for measuring forces and moments in three-dimensions simultaneously. A machine capable of doing this has been developed by Paquien (1978). Additional modifications to the machine were needed to enable *in vitro* measurement of forces and moments as applied in actual clinical settings. The most important modification was that of providing a gantry capable of three linear and three rotational movements so that duplication of the *in vivo* bracket-to-bracket positions could be made on the machine.

A similar, contemporary study to determine the effects of known applied forces systems and their resulting tooth movements using cuspid retraction as the chosen tooth movement will be reported elsewhere (Duff, 1987).

CHAPTER II

LITERATURE REVIEW

REVIEW OF LITERATURE

For tooth movement to be predictable, the clinician must deliver predictable force systems with optimum stresses on the periodontal ligament (Isaacson and Burstone, 1976). In order to determine what force system will produce optimum stress and predictable tooth movement, a combination of the principles of engineering, biology and orthodontic clinical techniques is necessary.

The purpose of this literature review will be to discuss the relevant historical developments as they relate to the quantification of tooth movement in response to known force systems. Factors such as biological and mechanical variables will be discussed also and the last section will be devoted specifically to molar uprighting, the tooth movement of interest in this study.

2.1 MEASUREMENT OF FORCE SYSTEMS

As early as 1917, Fish commented on the need to understand engineering principles as they apply to orthodontics. Since then, many techniques and devices have been developed to attempt to quantify force systems and resulting tooth movement so that the clinical and histological responses could be better understood.

(Burstone, 1969).

Lack (1980) discussed the many different devices that had been used to quantify force systems. These devices were mainly two-dimensional ways of measuring a three-dimensional force system. A brief review of the three-dimensional measuring systems is given below.

Teasley (1963) was the first to measure orthodontic forces in three dimensions simultaneously. An instrument, utilizing six strain gauges, resolved the force system into six components. The accuracy of the instrument was determined to be within 2 percent. However, this instrument indicated the "potential of the appliance tested and not necessarily the forces exerted on a tooth by the appliance."

Buck et al (1964) also used this machine to measure the force systems from a coil spring. However, no further reports in the literature using this machine have been found.

Burstone et al (1973) described a system of transducers, consisting of two semi-rigid bars to which strain gauges were applied, to record bending in all planes of space. This technique allowed a force system to be analyzed in three-dimensions. However, there were no further reports in the literature of data produced by this measurement device.

Solonche *et al* (1976) reported developing a device which rapidly measured uniplanar force systems from orthodontic appliances. They said that it could determine forces and moments from appliances which were statically indeterminate. Forces and moments were converted to linear and angular displacements respectively and then transduced to electrical signals. The accuracy of the transducers was reported to be better than 1%. Various springs were tested and the measured values were reported to be within 2% of the calculated value. However, no actual values were reported in this paper and there were no other papers with data from this device reported in the literature.

Paquien (1978) developed an instrument which, with subsequent modifications by McLachlan (1979) was capable of measuring three forces and three moments simultaneously. This force system was measured at the centre of resistance of a simulated tooth. Six strain gauge force transducers were used in conjunction with a mini-computer for the data acquisition and interpretation of data collected by the instrument.

This machine has been tested many times by independent investigators. Some of these investigations have included analyzing the forces produced by various cuspid retraction devices (Lack, 1980), by the so-called "light" wires (Sullivan, 1982), by the effects of ligation (Levin, 1985) and anchorage (Levine, 1985).

2.2 MEASUREMENT OF TOOTH MOVEMENT

There are many methods by which tooth movement can be recorded. These include intraoral and extraoral methods. Intraoral methods for recording tooth movement used calipers to make the measurements and, occasionally, an intraoral jig which has acted as the reference from which the intraoral measurements were made.

Burstone and Groves (1960), used specially designed calipers for intraoral use to measure retraction of anterior teeth by simple tipping. Andreasen and Johnson (1967), in studying molar tooth movement response to an asymmetrical headgear, used a spring bow divider to measure the distance from the lingual groove on the first permanent molar to a point on a stone jig which fit over the anterior teeth. This distance, between the ends of the divider, was then transferred to a sheet of paper and measured with a helios sliding caliper with 1/20 millimeter divisions. The standard error of measurement was reported to be 0.27 millimeters. Boester and Johnson

(1974) made direct intraoral measurements to record amount of space closure in cuspid retraction cases. No standrard error for their measurement technique was given. Huffman and Way (1983) measured tooth movement and tipping in cuspid retraction cases using dial calipers, a T-bevel and an acrylic jig (which capped the incisor teeth and rested on both the lingual tissues and the occlusal tip of the second premolar). Linear readings were made to an accuracy of 0.05 millimeters. Angular tipping movements were recorded to the nearest 0.5 degrees.

These intraoral methods for measuring tooth movement did not record the tooth movement in all three dimensions. Generally, a primary linear and, occasionally, a rotational movement was recorded. These intraoral techniques are almost impossible to use if accurate information regarding the three linear and three rotational tooth movements is desired. Also, the difficulties in obtaining stable reference landmarks and in repeatably identifying the same point for measurement reduce the accuracy of the final measurements.

More recently, holographic techniques have been used intraorally to accurately measure tooth displacement in three-dimensions (Pryputniewicz _et_ _al_, 1978; Pryputniewicz and Burstone, 1979; Burstone _et_ _al_, 1982).

The advantages of this technique were that it was non-invasive and that it was reported to be able to measure tooth movement to an accuracy of 0.05 micrometers in three-dimensions. However, this technique is valuable only for measuring initial tooth displacements over very short time intervals (i.e. 1-120 seconds).

Extraoral techniques involve replication of the intraoral tooth positions in two or three dimensions. Direct two-dimensional replications have been made using an intraoral photographic technique. Andreason et al (1984) used an Unitek Orthoscan II camera with Polaroid type 105 positive-negative film to measure three-dimensional movement as a result of using Nitinol archwires as initial alignment arches. However, the accuracy with which three-dimensional tooth movements can be measured from a two-dimensional photograph is questionable.

Three-dimensional replications of intraoral tooth position have been made using an impression technique. The resulting study casts could then be measured directly using various devices or could be photographed and then measured. However, reducing three-dimensional study casts to two-dimensional photographs (Biggerstaff, 1970; BeGole et al, 1981), makes accurate three-dimensional information regarding tooth movement difficult to obtain. Enlargement and distortion errors would be superimposed on the inaccuracies inherent in using an impression technique.

Various devices have been developed to measure directly from study casts in three-dimensions. It is important that three mutually perpendicular axes be developed so that tooth movement can be properly recorded. Jones *et al* (1980) also recognized that the same point on the subsequent study casts would have to be repeatably and accurately located using anatomical detail or acrylic templates if conclusions regarding tooth movement were to be made.

Simons (1924), one of the first to develop a three-dimensional measurement technique, utilized the symmetrograph to measure tooth movement from study casts in three-dimensions.

Savara and Sanin (1969) used a modified comparator and decimal converter connected to an IBM key punch to record landmarks independently. This technique allowed measurements to be made from photographs, xerox prints or study casts. A range of accuracy of 0.01 to 0.47 millimeters was found depending on the tooth measured.

Van Der Linden *et al* (1972) described a three-dimensional measurement technique utilizing the Optocom. This device consisted of a microscope mounted over a two-dimensionally movable table. A dental cast attached to a base could be placed on the sliding table in a fixed position using precision pins and holes. Marked points on the cast were aligned in the centre of two cross wires in the microscope. In this manner, two dimensions were recorded. The third dimension was recorded after placing the cast vertically in a slot. They reported that 387 points could be measured in about 20 minutes. The accuracy was said to be high but actual values were not given.

In 1976, Moyers et al used the Optocom to collect data for their Standards of Human Occlusal Development. They noted that proper location of cusp tips was difficult because a monocular eyepiece makes depth perception difficult. The points to be recorded were marked with a special drawing pencil in order to make identification easier.

Butcher and Stephens (1981), Takada et al (1983) and Richmond (1987) investigated the "Reflex Metrograph (H.F. Ross, Salisbury, Wiltshire, England) as a new means of measuring dental casts in three dimensions. The cast to be measured was placed in front of a semireflecting mirror. Measurement of a marked point on the dental cast was made by aligning a moveable light source, 0.3 millimeters in diameter, with the marked point. The light source was carried on a three-dimensional slide system which allowed it to be digitized. Butcher and Stephens (1981) found measurement errors to be approximately 0.128 millimeters in the mesio-distal direction, 0.299 millimeters in the vertical direction with the greatest variation in the bucco-lingual direction of 0.353 millimeters. However, Takada et al (1983) reported that even operators with no previous experience could determine points to an accuracy of +/- 0.1 millimeters. They also said that the measurement could be made either with the naked eye or with the aid of binocular magnifiers (Gullstrand Loupe, Jena Instruments, Ltd., Surrey, British Columbia). No mention was made of any improvement in accuracy using the binocular magnifiers. Richmond (1987) found that 110 points could be recorded in less than 20 minutes when an experienced operator did the measurements.

Furukawa (1984) investigated the reproducibility and identification of tooth marks from alginate impressions of maxillary and mandibular arches poured in dental stone. A VECTRON MODEL VSC-14 (Kosaka Manufacturing Company) was used to record the coordinate values of the x, y, and z coordinates up to five digits. Repetitive precision of the original point at each axis was found to be +/- 0.1 millimeters. Accuracy of arbitrary points was found to be +/- 0.2 millimeters and that of length measurements, +/- 0.4 millimeters.

Extraoral methods involving direct measurements from study casts seemed to have similar accuracy. Thus, no one technique appeared superior to any other. Differences in the technique appeared to be more related to the ease with which they could be used and the time taken to measure a certain number of landmarks. Perhaps the reason for the similarities in the techniques was related to the inherent inaccuracies of impression techniques as well as difficulties in repeatably and accurately locating a point on the study casts.

2.3 FACTORS AFFECTING TOOTH MOVEMENT

Factors affecting tooth movement include both biological variability and mechanical variability. These will be discussed further below.

2.3.1 BIOLOGICAL VARIABILITY

The exact nature of the biologic response to applied force systems remains unknown at the cellular level (Rygh, 1973). It is important to establish a correlation between stress patterns and biologic response (Schwartz, 1932; Oppenheim, 1944; Reitan, 1951; Utley, 1968; Rygh, 1973; Storey, 1973) so that the best force system for a particular type of tooth movement may be used.

Biological variability, though used frequently, has not been exactly defined. It seems to be applied to situations where a more exact explanation of human response to orthodontic mechanotherapy is lacking.

One major biological variable is the size and shape of the tooth/teeth and surrounding alveolar bone. Burstone <u>et al</u> (1961) reported that variations in root length, diameter and contour may be important factors when assessing tooth response to applied forces systems. Hixon and Klein (1972) said the size of tooth roots could vary by as much as a factor of two when like teeth were compared between individuals. This variation would affect the location of the centre of resistance of the tooth which in turn would affect the tooth's response to an applied force system (Burstone <u>et al</u>, 1961). Thus, Stoner (1960) suggested that not all teeth may require identical forces to move them.

Variations in the density of the surrounding bone may also be a factor in tooth response to force systems (Gianelly and Goldman, 1971; Reitan, 1985). Profitt (1986) said that cortical bone is more resistant to resorption. Thus, tooth movement is slowed when a root contacts it.

Another biological variable is the cellular response which occurs as a result of the applied force system. An intact vascular system and a potential source of cells which can be activated are necessary for tooth movement to occur (Moyers and Bauer, 1950; Burstone et al, 1961; Schwartz, 1967; Gianelly and Goldman, 1971; Hixon and Klein, 1972; Reitan, 1985).

Reitan (1957, 1960) found differences in tissue response within subjects of similar age groups and between subjects of different age groups. He suggested that this may be because adults have alveolar bone that is more dense than bone in younger patients. Lack of marrow spaces, seen more often in adults, indicated fewer bone-forming/resorbing elements in their periodontal ligaments. Storey (1973) also supported Reitan by considering age as well as sex, hormones and diet to be factors affecting rates of tooth movement.

Carey, in 1944, may have recognized that tooth movement was time-dependent when he commented that bone tissue which had been disturbed allowed more tooth movement. Data by Reitan (1957) and Burstone (1962a) showed that the rate of tooth movement was not constant. Gianelly and Goldman (1971) and Burstone (1962a) demonstrated that tooth movement occurred in three stages. The first stage occurred immediately after force application and lasted while the tooth moved rapidly over a short distance. This movement may have represented the displacement of the tooth in the periodontal membrane space as well as bending of the alveolar bone. Experimental evidence suggested that light and heavy forces displaced the tooth approximately the same amount in this initial phase. The second phase was a delay period during which little or no tooth movement occurred. Possibly, alveolar bone resorption took place during this phase. The third stage occurred when the tooth moved quickly into the small space vacated by alveolar bone resorption. This process was then repeated.

2.3.2 MECHANICAL VARIABILITY

There are many factors in the design and construction of orthodontic appliances that could influence the direction and magnitude of the applied force systems. Many of these factors are well-known and are widely reported in the literature. However, tooth movement in response to seemingly similar appliances is still variable (Irish, 1927; Orban, 1936; Oppenheim, 1936).

One of the most obvious mechanical variables is due to inconsistencies in the manufacturing process of the appliances used. Burstone et al (1961) found significant variation in different batches of supposedly identical diameter archwires. In addition, Hixson et al (1982) found that wires assumed to be rectangular often had bevelled edges. This led to large amounts of play, or deviation angles, of the arch wire in the brackets when measured angularly (Creekmore, 1979; Hixson et al, 1982; Thurow, 1982). This deviation angle could range from 0.2 to 12.9 degrees (Sebanc et al (1984).

Raphael et al (1981) and Lang et al (1982) commented on the variability of molar tube sizes. They compared the theoretical degree of rotation of various arch wire/tube combinations to an actual measured amount and found that the measured amounts of rotations were always higher. Lang et al (1982) said that this was because the wires used were always slightly smaller than their stated dimensions and that the internal lumen dimensions of the buccal tubes were larger than their stated dimensions. Thus, manufacturing inconsistencies were found to be a factor in loss of force control in appliance force delivery (Dellinger, 1978; Lang et al, 1982; and Sebanc et al, 1984).

A second mechanical variable is the type of appliance chosen for force delivery. Comparisons of rates of tooth movement from frictionless versus friction-involving appliances could lead to erroneous conclusions.

Factors influencing friction include fit of the archwire in the bracket slot (also related to archwire size and bracket width), ligature tension, interbracket distance and surface irregularities (Stoner, 1960; Paulson et al, 1970; Kamiyami and Sasaki, 1972; Newman, 1972; Andrews, 1975; Riley, 1979; Frank and Nikolai, 1980; Andreason and Zwanziger, 1980; Sullivan, 1982; Thurow, 1982; Garner et al, 1986).

There has been controversy as to the significance of friction intraorally due to tooth jiggling, lubrication from saliva and masticatory as well as other oral forces (Hixon et al, 1969 and 1970). Stannard et al (1986) reported that for a liquid to reduce friction it must be a lubricant. They found that the type of wire material determined whether saliva reduced or increased friction. Stainless steel's coefficient of friction in artificial saliva was found to increase. Andreason and Quevedo

(1970) found no difference when a variety of frictional producing situations were compared under wet and dry conditions. Jarabek and Fizzell (1972) said that the reason friction occurred was because the archwire and bracket usually contacted at one or more small areas. Any lubricant present would be easily squeezed out from the contact area with no reduction in friction.

Obviously, there has been a lack of agreement on the role of friction in force delivery. In molar uprighting, when distal crown movement is desired using a continuous archwire, the distal crown movement on this archwire may introduce frictional effects, which may become an important variable in this case.

A third mechanical variable is due to variations in operator technique. Hixon et al, 1969; Hixon et al (1970), White et al (1979), Dellinger (1978) and Sebanc et al (1984) recognized variability in bracket placement, partly due to the variation in tooth profile and size, as being a factor in lack of control of applied force systems. An additional factor was variability in appliance formation due to operator inconsistency (Mahler and Goodwin, 1967; Steyn, 1977; White et al, 1979). Certain types of springs and loops are inherently more difficult to form and thus, to duplicate, which could result in a wide variety of force systems being expressed. Thus, a large range of clinical results may occur.

A fourth mechanical variable was the actual magnitude and site of the applied force (Hixon and Klein, 1972) as well as the desired direction of tooth movement and the number of teeth incorporated into the appliance (Stoner, 1960; Gianelly and Goldman, 1971). Hixon and Klein (1972) reported that the degree of tipping of the tooth and subsequent bone bending influenced the rate of tooth movement. Hocevar (1981) said that interbracket span was one of the most important determinants of the force levels inherent in an appliance. Section 2.4 discusses the wide range of force levels and types considered desirable for particular tooth movements.

2.4 OPTIMUM FORCE

Optimum force has been defined as that force which produces:

1. a rapid rate of desired tooth movement;
2. a maximum biologic response (direct bone resorption needing no time for repair);
3. minimum damage to the oral tissues; and
4. minimum patient discomfort.

(Smith and Storey, 1952; Storey and Smith, 1952; Burstone, 1962a, 1966; Hixon *et al*, 1969; Jarabek and Fizzell, 1972; Gianelly and Goldman, 1971; Isaacson and Burstone, 1976)

Burstone (1985) redefined optimum force as the force that accurately controls the centre of resistance of a tooth during tooth movement, produces optimal stress levels in the periodontal ligament and maintains a relatively constant stress level as the tooth moves from one position to the next. Additional factors that must be included when considering an optimum force for tooth movement are the presence of interfering forces of occlusion or other muscle forces (Stuteville, 1938). "A very strong case can be built for understanding and knowing the magnitude of force delivered for different types of tooth movement. Since force magnitude is one of the variables that the orthodontist can control during treatment, it is one that he should take full advantage of in his clinical procedures." (Burstone, 1962a)

There has been great controversy in the literature as to what force types and levels are actually the best for specific tooth movements. Table I reviews the experiments and results for many of the important studies that have attempted to relate force magnitudes and/or force types to tooth movements. Most of the studies involved cuspid retraction as the desired tooth movement.

TABLE I

AUTHOR	MEASUREMENT TECHNIQUE	MECHANICS	FORCE LEVEL	FORCE TYPE	RESULTS
Schwartz (1932)	histologic	dog premolar teeth using calibrated spring	Gentle (20-26g/cm²)	constant	F applied should not occlude blood supply. An optimum F does exist.
Orban (1936)	histologic	dogs, monkeys, humans	used strong intermittent F but recommends cont.	Continuous	Continuous F is biologic preference because it will not reduce activity of resorbing connective tissue
Oppenheim (1936a,b) (1944)	histologic	humans, monkeys -used expansion arch	Light	1936-Intermittent; 1944-Continuous.	Reversed original decision that intermittent F best but said that because light continuous F could not be done clinically, intermittent F were still best.
Paulich (1939)	lit. review	-	<25g/cm²	Continuous	(Supported Schwartz (1932)) Also said that heavy F could be tolerated only if they were applied intermittently.
Hemley (1941)	root resorption study		Light	Intermittent	Light intermittent F resulted in low root resorption.
Sved (1948)	No experimental proof			Intermittent	Intermittent F avoided bone trabeculae rearrangement.
Smith and Storey (1952)	calipers used intraorally	4-10 weeks of cuspid retraction on 8 patients	150-200g is optimum F for cuspid retraction Range: 175 to 600g	Continuous	At F<150g: no tooth movement. At F>300g: molar movement. More cuspid movement occurred with lighter than with heavy forces. Said an optimum F does exist to produce maximum tooth movement.
Reitan (1957)	histologic	humans	F level depends on desired movement	Continuous	25g: mx ant extrusion 130g: torquing F at apex 150-250g: mx cuspid translation 100-200g: md cuspid transe

TABLE I (cont'd)

Weinstein and Haack (1959)	-	human pre-molars	2 g	-	No one optimum F exists. F<2g can cause tooth movement.
Stoner (1960)	lit. review	-	-	-	No one optimum F exists. A F good for one type of movement may be ineffective or traumatic for another.
Burstone and Groves (1960)	intraoral calipers	retraction of anterior teeth by tipping on 22 patients	25 to 150 g per quadrant	Continuous	Optimum F=50-75g/quadrant for maxillary anterior retraction with no increase in rate of tooth movement above this value.
Newman (1963)	lit. review	-	Light (28-113g)	Continuous	Light continuous F resulted in direct alveolar bone resorption while heavy intermittent F resulted in undermining resorption.
Anderason and Johnson (1967)	calipers intraorally Reference: incisors	12 weeks of asymmetric headgear on 14 patients	200g vs 400g	Continuous	Increased F causes increased rate of tooth movement
Utley (1968)	superimposed radiographs	cuspid retraction (21 cats) -using elastics	Light F= 40-60g Moderate F= 135-165g Heavy F= 400-500g	Continuous	Each animal had independent rate of movement regardless of F magnitude. Teeth on different sides of same animal moved equal distances regardless of F.
Hixon et al (1969)	calipers on models Reference: 25 deg cephs & osseous implants	8 weeks of cuspid retraction measured on 8 subjects	Range: 64 to 1515g	-	Increased F = increased rate of tooth movement up to 300g.
Hixon et al (1970)	calipers on models Reference: 25 deg cephs & osseous implants	8 weeks of 3X/week for cuspid retraction measured on 6 subjects	Range: 0 to 1000g	-	Higher F resulted in larger tooth movement.

TABLE I (cont'd)

Ackerman et al (1969)	-	-	Light F= 50-75g Heavy F>150g	-	No single optimum F exists.
Fortin (1971)	histologic	dog premolars	Range=147 to 450g	Continuous	Light continuous F best for good tissue response.
Sleichter (1971)	intraoral (Boley Gauge)	md cuspid retraction	Light=150-200g Heavy=1200-1500g	Continuous	Light F move teeth at same rate as heavy F.
Boester and Johnson (1974)	calipers intraorally & models Reference: 22.5 deg cephs	10 weeks of cuspid retraction on 10 patients	Range: 57 to 312g	Continuous	Above 140g of F there was no increase in the rate of tooth movement. No data to support optimum F theory or differential F concepts as relative anchorage loss was independent of F magnitude used.
Andrews (1975)	lit. review	-	600g is optimal F	Continuous	The optimum F of 600g takes into account frictional F of tooth sliding along wire.
Andreason and Zwanziger (1980)	calipers used intraorally Reference: incisors	10 weeks of cuspid retraction on 14 patients	Light F: 100-150g Heavy F: 400-500g	-	Heavier F showed greater movement of anchorage unit.
Huffman and Way (1983)	intraoral measurement using dial calipers	25 arches on 16 patients over 10 weeks	Compared 200g F on 0.016 and 0.020 wires	Continuous	No difference in rate of tooth movement on these 2 wire sizes but 0.020 showed less tipping.
Burstone (1985)	lit. review	-	-	-	No data exists to support the theory that an optimum F exists.

It was generally felt that cuspid retraction would be the tooth movement most likely to evenly distribute the forces in the periodontal ligament.

Perhaps some of the difficulties in determining optimal force levels have been due to the biological and mechanical variables discussed previously. Also, the fact that the rate of tooth movement changed as the applied force changed during deactivation of appliances (Storey and Smith, 1952) could be another contributing factor to difficulties in determining optimum forces.

2.5 CLINICAL TECHNIQUES: MOLAR UPRIGHTING

In this investigation of tooth movement in response to known applied force systems, molar uprighting was chosen. Thus, it was necessary that an appliance be used which would allow accurate determinations of the applied force system to be made. A segmental technique, developed by Burstone in 1966 when he expanded the differential force concept (Begg, 1956), was used to overcome the problem of the inherent statically indeterminate nature of the continuous arch wire (Sved, 1952; Burstone, 1962a; Burstone *et al*, 1973; Koenig and Burstone, 1974a; Isaacson and Burstone, 1976; Sullivan, 1982). The principles of the segmental technique involved using "two-tooth" segments which allowed calculation of the applied forces as the system was now determinate (Burstone et al, 1973). If the anchorage segment could be rigidly held together, it could be considered as one tooth and the molar requiring uprighting as the other tooth.

Use of the segmental technique also allowed multiple cross-sections of wire to be used (Burstone, 1962a, 1982). Thus, areas requiring increased flexibility, such as in the active appliance, could be made in wire of smaller cross-sectional dimensions. Areas requiring increased rigidity, such as those used in the anchorage segment, would have stiffer wires (Steiner, 1953) to provide greater control.

2.5.1 ANCHORAGE OR "REACTIVE" TEETH

In attempting to measure tooth movement, the problem of establishing a stable reference system had to be considered as such a reference system does not exist in the oral cavity. A rigid anchorage unit might provide a reasonably stable segment from which tooth movement could be measured. Some of the definitions and considerations of anchorage are presented.

Thurow (1982) defined anchorage as "the supporting base for orthodontic forces that are applied to stimulate tooth movement; the area of application of reciprocal forces that are generated when corrective forces are applied to teeth." All other things being equal, he felt resistance to movement was directly proportional to root area and could be enhanced by the manner of interlocking of the cusps (occlusion), the bone in which the teeth are situated, muscular pressure and growth direction of the teeth.

Graber (1972) and Thurow (1982) said that, intraorally, there was no true anchor unit. Therefore, anchorage depended on the skill with which the clinician could manipulate the force systems and orthodontic appliance to produce tooth movement only in the desired areas.

Burstone (1962) enhanced the anchorage unit by using stabilizing wires of heavier dimension possibly with palatal and lingual arches (Koenig and Burstone, 1974). Tulloch (1982) said that a lingual arch is mandatory when uprighting tipped molars in the mandibular arch to help provide resistance for the uprighting movement. In addition, "all teeth as far forward as the canine in the treatment quadrant should be banded and should carry an edgewise bracket of suitable width."

Roberts et al (1982) said, that in addition to using a lingual arch for increased anchorage, the mandibular incisors could be bonded to the lingual arch thus further increasing the stability of the anchor segment. This technique is particularly recommended in cases where the teeth are periodontally compromised.

These concepts were applied in this investigation in the preparation of the anchorage segment.

2.5.2 <u>ACTIVE APPLIANCE</u>

The part of the appliance that delivers the force system to produce a desired tooth movement is the active appliance. Burstone (1975) has said that the "active" member in the segmental technique should possess:

1. **Low Load Deflection Rate:** [or Low Force/Unit Activation (Burstone, 1961 and 1975) or Low Spring Rate (Marcotte, 1973) or Low Spring Constant or Low Stiffness (Thurow, 1982)] Burstone (1975) described a low load deflection rate as desirable because:

   (a) it maintained a greater more stress level in the periodontal ligament; and

   (b) it offered greater control in force magnitude (i.e. a small change in deflection does not significantly alter the force delivered).

2. **High Maximum Elastic Load:** This represents the

highest load that can be placed on a spring or wire without permanent deformation. A high maximum elastic load was important to prevent permanent deformation or breakage during activation of the appliance or from spurious forces generated during mastication.

3. **Long Working Range:** This was a measure of the extent to which a spring or wire could be deflected without exceeding the maximum elastic load. According to Burstone (1975), Jarabek and Fizzell (1982) and Thurow (1982), a long range of activation was desirable because the amount of tooth movement between adjustments was maximized. This is supported by Paulich (1934), Jacobson (1966), Newman (1963), Jarabek and Fizzell (1972), and Thurow (1982).

Design of the active member would also be influenced by the limitations of the oral cavity such as whether it was irritating to the soft tissue, unhygienic, uncomfortable and/or overly complicated to fabricate and use (Burstone, 1962b).

In addition, other factors that must be defined when determining the force system for a particular tooth movement include the magnitude of the force, direction of the force, point of application of the force, distance over which the force acts and uniformity of the force within this distance (Burstone et al, 1961).

There are many appliances reported in the literature for uprighting tipped molars (Norton and Proffit, 1968; Khuow and Norton, 1972; Burns, 1973; Tuncay et al, 1980; Roberts et al, 1982; Tulloch, 1982; Simon, 1984). These include a plain archwire with compressed coil springs, helical uprighting spring, T-loop appliance, box spring appliance and Burstone uprighting spring. However, no three-dimensional analysis of the force system produced for an uprighting situation using these loops was presented. If and when the descriptions of force systems were given, they were calculated from theoretical examples of force and moment delivery. Thus, no actual measured data could be used to determine which appliance was the "best" for uprighting molars. When uprighting molars, the design of the appliance used should be varied according to the intended tooth movement (Tulloch, 1982). However, until one knows which appliance will deliver the appropriate force system to produce the intended tooth movement, correct appliance selection cannot be made.

2.6 CONCLUSIONS

Many factors have to be controlled before conclusions can be made as to whether or not tooth movement in response to known force systems is as variable as reported in the literature. Thus, it was unlikely that only biological parameters would affect rate of tooth movement in different patients. More likely, mechanical variables affecting the applied force system were contributory as well, making the force system applied to the teeth unknown (Reitan, 1957 and 1985; Gianelly and Goldman, 1971). The question of optimum forces for desired tooth movements is a long way from being answered.

Thus, to analyze and know applied force systems and resulting tooth movement, it becomes necessary to have the proper equipment so that meaningful data can be obtained. To this end, the machine developed by Paquien (1978) was used in this investigation.

The literature review on methods of tooth movement measurement revealed that, unlike the force and moment measurement techniques, several methods of measuring tooth movement within approximately the same error range existed. Selection of the most appropriate method, or development of a new method, would involve factors such as time needed to record change in tooth position on the casts, ease of locating landmarks and accuracy with which this could be accomplished.

This investigation brings together information from known applied force systems measured in three dimensions simultaneously with information regarding tooth movement, also measured in three dimensions. In this manner, the question of optimum force for a specific tooth movement may begin to be answered. The results of this study may also provide a challenge to current orthodontic treatment techniques which often involve increasing archwire dimensions using preformed arch forms to attain final tooth positions which can never be predicted. Maybe successful orthodontic treatment will come to be judged by how accurately a predetermined final tooth position can be attained by delivering an accurately determined force system. This would move orthodontics from an empirical science into a more quantitative science.

CHAPTER III

MATERIALS AND METHODS

MATERIALS AND METHODS

3.1 INTRODUCTION

This investigation was undertaken to develop a technique whereby in vivo tooth movement could be evaluated and related to applied forces and moments measured simultaneously in three-dimensions. As discussed in the literature review, several authors have described tooth movement in response to force systems in two-dimensions. Therefore, in order to move from two dimensions to three dimensions, some major changes in thinking and technique were in order. Furthermore, the virtual impossibility of intra-oral three-dimensional measurements necessitated replication of the clinical configurations in an in vitro setting with enough accuracy to allow three-dimensional analysis to be made.

Molar uprighting was chosen as a means of examining tooth movement in response to known applied forces and moments because:

(a) it generally involves a relatively large movement of the crown of a tooth making measurement errors of +/-0.1 mm acceptable.

(b) there is little published data on the three-dimensional analysis of forces and moments resulting from molar uprighting appliances.

Although not the primary objective of this investigation, it was hoped this investigation would provide more information on this subject;

(c) it is a typical tooth movement in orthodontics particularly now that orthodontic treatment of adults has become more common.

as the forces of occlusion on the molar to be uprighted are relieved by splints or occlusal reduction, and as facial growth is not a consideration in the adult, molar uprighting is a good clinical situation in which to evaluate results of moment and force applications (Roberts *et al*, 1982).

As mentioned previously, intraoral constraints and the complexity of three-dimensional force and moment analysis precludes *in vivo* measurement. Therefore, a combined *in vivo*-*in vitro* approach was needed in order to be able to measure the applied forces and moments delivered by an appliance to a tooth *in vivo*. Fortunately, a machine which permitted three-dimensional force and moment measurements *in vitro* was available. However, a method was required for transferring the *in vivo* force system to this machine. In outline, this transfer was achieved by comparing a replica of the appliance and of the tooth-to-tooth bracket positions at several stages in the treatment sequence. These replicas were readily analyzed in the *in vitro* machine.

As stated, a technique had to be used whereby tooth movement could be measured *in vitro*. An impression/stone model technique was adopted. In this way, a permanent record of the movement achieved between appointments was available for reference, replication of measurements and calculation of errors.

It was hoped that, with subsequent refinements of this technique, longitudinal data could be collected relatively easily for different types of tooth movement. In the future, more precise knowledge of tooth movement in response to known force systems would be possible.

The remainder of this chapter will discuss the *in vivo* techniques for data collection, the method of transferring the *in vivo* data, the system for *in vitro* analysis and the methods used to analyze the tooth movement data.

3.2 IN VIVO EXPERIMENTAL PROTOCOL

3.2.1 PATIENT SELECTION

The long-term goal is to examine sufficient patients to provide data on tooth movement which would have general validity. However, in this work, the primary objective was that of developing techniques that would provide reliable data on force systems and the resulting tooth movements. For this reason it was felt that seven molars needing uprighting would be sufficient to develop and test the new techniques.

In order to attempt to control some of the variables which would make comparison of the data between patients more meaningful, the patients were chosen on the basis of the following criteria:

(1) the molar to be uprighted was the only tooth in that quadrant distal to the edentulous space.

(2) the molar to be uprighted had no large restorations;

(3) the periodontal health was good. Periodontal health was based on a radiographic examination showing good alveolar bone levels surrounding the teeth. Clinical examination for plaque, calculus, gingival colour, contour and pocket depth was consistent with a diagnosis of a healthy periodontium. The patient was given oral hygiene instruction once the orthodontic appliances were in place;

(4) the patient had to be assessed as reliable because missed appointments, poor oral hygiene and/or broken

appliances would reduce the value of the collected data;

(5) the patient had to be able to tolerate a mandibular splint (see section 3.2.2 for more details);

(6) the patient had to be able to tolerate the making of alginate impressions without moving or attempting to withdraw the impressions as these impressions were used to make the casts from which tooth movement was to be measured;

(7) the patient had to sign a consent form approved by the Ethics Committee at the University of Manitoba which allowed the information gained from impressions, etc. to be used for research purposes.

3.2.2 APPLIANCE DESIGN

Teeth in the anchor segment, (teeth other than the molar(s) to be uprighted) formed the reference against which the molar movement was measured. Hence, their stability became a major consideration. In order to minimize anchor segment movement the following mechanics were used:

(1) The use of segmental mechanics to upright the tipped molars allowed a better anchorage unit to be achieved. The active component of the segmental uprighting

appliance was placed into the molar bracket and, depending on which tooth was available and on space requirements, the reactive component of the segmental uprighting appliance was attached to a first or second bicuspid

(2) A fixed (soldered) lingual arch made of 0.914 mm (0.036 inch) stainless steel was used. It extended from the reactive tooth (the bicuspid tooth which received the reactive end of the molar uprighting appliance) to either the reactive tooth on the opposite side (for bilateral molar uprighting cases) or to another suitable tooth on the contralateral side. The lingual arch contacted the lingual surfaces of all of the anterior teeth between the abutments.

(3) Patients had 0.457 X 0.635 mm (0.018 X 0.025 inch) Ormco[1] brackets bonded to all anterior teeth and Unitek[2] bands cemented to bicuspids and molars except for the reactive bicuspid and molar to be uprighted.

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[1] Ormco: 1332 South Lone Hill Ave.
Glendara, Calif. 91740

[2] Unitek: 2724 South Peck Rd.
Monrovia, Calif. 91016]

[3] Burstone bracket: Ormco (Cat. # 181-1825)

The reactive bicuspid had a Burstone bracket[3] soldered onto a blank Ormco bicuspid band. An "A" Company[4] convertible bracket-tube, prewelded to an "A" Company first molar band, was cemented on the active tooth (which was always a second or third mandibular molar). The tube was converted into a bracket by removing the welded conversion tabs. Thus, direct access of the wire into the molar bracket slot was obtained and helped to prevent distortion of the loop when ligating it into the active and reactive teeth. Also, there would be less "play" in the bracket than in a tube as ligation could be done so as to have the wire held firmly against the base of the bracket.

Initially, the tube on the bicuspid was used to hold the reactive arm of the loop to be measured. However, this had to be abandoned early in the test for it was found that this tube was actually 0.559 X 0.711 millimeter (0.022 X0.028 inch). Thus, the vertical height of the tube in this bracket was 0.102 mm (0.004 inch) larger than the wire dimension of

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[4] "A" Company: 2155, boul. Pix IX
Montreal, Que. H1V 2E4

0.457 mm (0.018 inch). Subsequently, the reactive arm of the loop to be measured was placed into the slot of the bicuspid bracket and ligated. This modification necessitated placing the main arch wire of the anchor segment into the tube of the bicuspid bracket-tube attachment.

A large dimension main arch wire (0.432 X 0.635 mm (0.017 X 0.025 inch) stainless steel from Ormco) was bent to fit the malocclusion. Alignment of anchor teeth was not attempted at this stage as it was felt that teeth that had not been moved would provide better anchorage than teeth that had a previous bone disturbance (Carey, 1944). Once the passive arch wire was ligated, it was allowed to "settle" for four to six weeks so that any slight activation in this wire could work out becoming passive.

(4) A mandibular acrylic splint, formed on a Biostar Pressure Molding Machine[5], and constructed with 3 mm thick acrylic[6] was used to:

(a) prevent occlusal contact between the molar(s) to

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[5] available from Great Lakes Orthodontic Products Inc.:
1550 Hertel Ave.
Buffalo, N.Y. 14216

[6] Biocryl (Clear): Great Lakes Orthodontic Products Inc.

be uprighted and teeth in the opposing arch;

(b) provide additional stability to the anchor segment, and

(c) provide a check on the stability of the anchor unit. If the splint became unstable, it could be assumed that the anchor teeth had moved.

3.2.3 FORCE DELIVERY SYSTEM

Loops generally used in the Graduate Orthodontic Clinic (U of M) for clinically uprighting mesially tipped molars were tried. There was no attempt to be exhaustive in the selection of appliances that were tested or to select appliances that were thought to be better than others. Thus, some of the criteria used in selection of appliance design were:

(1) that the appliance should be symmetrical in shape so that equal and opposite moments could be applied during the activations;

(2) that the appliance should encounter no interference from the surrounding gingival and vestibular tissue;

(3) that adequate space should exist between the molar to be uprighted and the last tooth in the anchorage segment.

Thus, the appliances studied were the Burstone

Uprighting Spring (referred to as BUS) and the T-loop (see Figure 1).

The wire size used for the activated appliances in this investigation was limited to 0.457 mm (0.018 inch) square stainless steel[7] wire. This square wire would fit closely into an 0.457 mm (0.018 inch) slot in the vertical dimension. This combination of wire and bracket system was considered satisfactory to provide the required force delivery and control.

3.2.4 IMPRESSION TECHNIQUE

Impressions were made of the patient's tooth relationships at each appointment using "Fast Set Alginate"[8] following manufacturer's directions. This impression material was the same as that routinely used in the University of Manitoba graduate orthodontic clinic. Models were cast from the impressions in orthodontic plaster[9], using standard manufacturer's techniques. Ease

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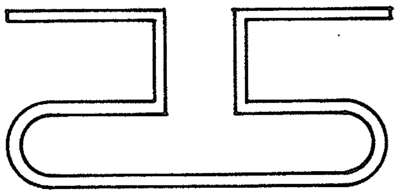
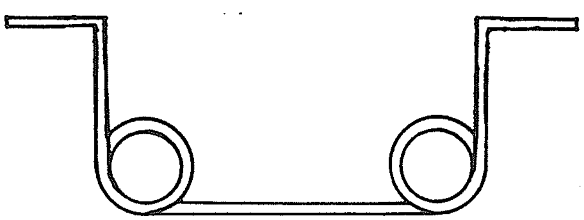
7 Wires kindly donated by Ormco.

8 Jeltrate Plus Type I - Fast Set (manufactured by The L.D. Caulk Company); Division of Dentsply International Inc., Milford, Delaware 19963

9 Orthodontic Plaster (manufactured by Modern Materials Orthodontic Plaster) from Columbus Dental, Div. of Mills Lab Inc. 1000 Chouteau Rd., St.Louis, Mo. 63188



T-LOOP



BURSTONE UPRIGHTING SPRING (BUS)

Figure 1: Loops used in molar uprighting investigation.

of handling, familiarity with the impression materials, and general use in the orthodontic clinic (so that data collection for certain procedures might become a routine part of the clinic program) were considered important factors in this process.

The absolute stability of the materials used was not considered to be critically important as the measurements were made from cast to cast rather than from patient to cast. Therefore, as long as the technique of manipulation was constant, dimensional changes would be approximately the same in each cast.

3.2.5 TECHNIQUE FOR IN VIVO-IN VITRO TRANSFER

Five patients were selected for this molar uprighting study. Two patients had bilateral molars to be uprighted so that a total of seven molars was investigated. Each patient satisfied the criteria described in section 3.2.1.

At each appointment, an alginate impression was made of the arch containing the molar to be uprighted and a plaster cast was poured from this impression. This cast formed the record of tooth position from appointment to appointment and allowed the analysis of the effect of the applied forces and moments to be quantitated in terms of tooth position.

In order to record the in vivo bracket-to-bracket position of the uprighting molar and the reactive tooth, a passive wire template was made at each appointment (see Figure 2). Initially, several different techniques were examined, each of which involved making a passive fit of a full-dimension arch wire between the two appropriate brackets. Finally, a method using two pieces of wire joined by Jet Ortho Acrylic[10] provided an accurate replication of the in vivo relationship. Two short lengths of wire with stops to prevent them from sliding in the brackets were ligated into the brackets, one on the active tooth and one on the anchor (reactive) tooth. Both ends of the wire between these two teeth were bent into a circle and allowed to approximate, but not contact, one another. Jet Cold Cure Acrylic was then allowed to encompass the ends of these wires so as not to disturb their passive relationship but to fix this relationship. Thus, when cured, the acrylic firmly held the two wires and therefore, permitted removal of the constructed passive wire template and subsequent replication of the bracket-to-bracket relationship in vitro.

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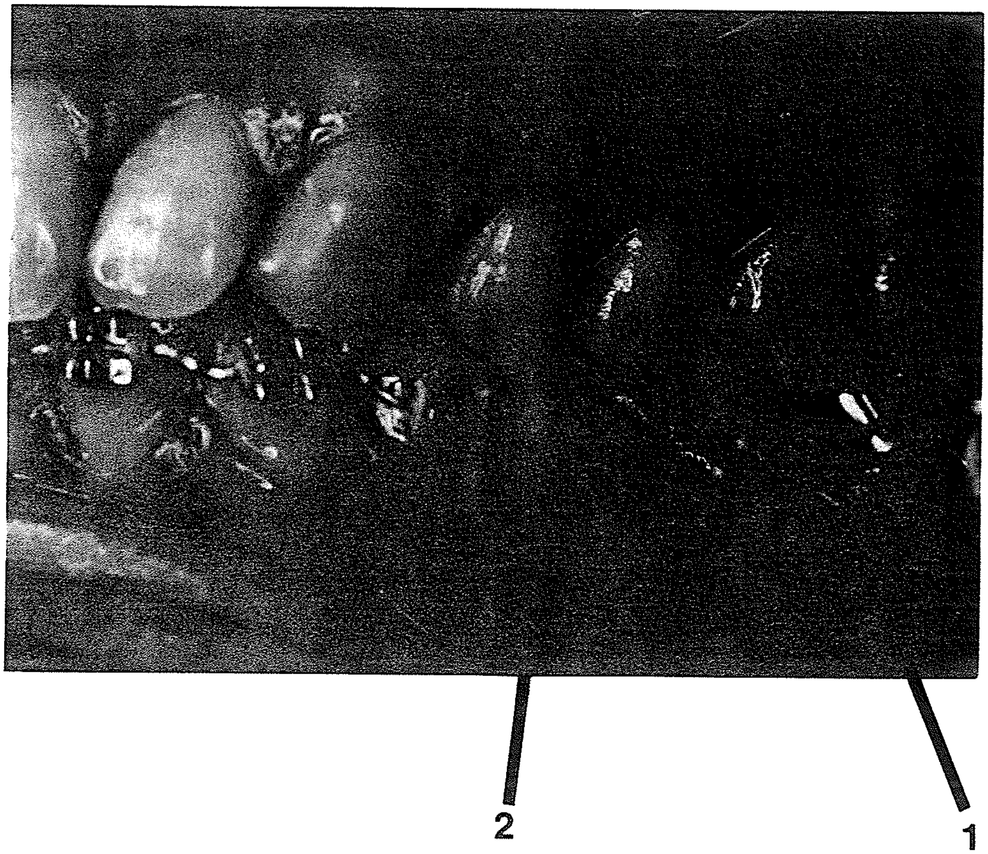
[10] Lang Dental Mfg. Co. Inc.
Chicago, Ill. 60610, U.S.A.



1. Molar wire segment with stop mesial to molar bracket.
2. Bicuspid wire segment with stop mesial to bicuspid bracket.
3. Jet Cold Cure Acrylic encompassing both circular ends of the wires.
4. "Active" tooth.
5. "Reactive" tooth.

Figure 2: Passive template <u>in vivo</u>.

Two identical "active" loops were made to fit passively into the existing intra-oral configuration so that activation bends could be placed into the wires. Activations varied from 30 to 45 degrees but were generally 45 degrees to the passive state. Both ends were always activated through the same angle but of opposite signs. No attempt was made to place additional counter bends to prevent spurious tooth movement in the uprighting molar.

The duplication of these two active loops was verified in two dimensions using a geometric template drawn on paper. The third dimension was duplicated by holding the two active loops together and visually making appropriate adjustments. One of these active loops was then ligated into the patient to produce tooth movement and the other active loop was placed in the *in vitro* duplicate molar-bicuspid bracket relationship to determine the initial force system applied to the tooth. The underlying assumption was that the two loops would produce nearly identical force systems when each was activated to the same degree. Clearly, this assumption had to be tested. The method and results of this testing are given in Appendix A. The results showed that the loops could be duplicated to within a +/- 20% tolerance.

At each appointment, the above procedure was repeated until the molar was upright, at which point, data collection for this study was discontinued. The patient then continued to receive the necessary orthodontic treatment to correct the remainder of his/her malocclusion.

3.3 IN VITRO EXPERIMENTAL PROTOCOL

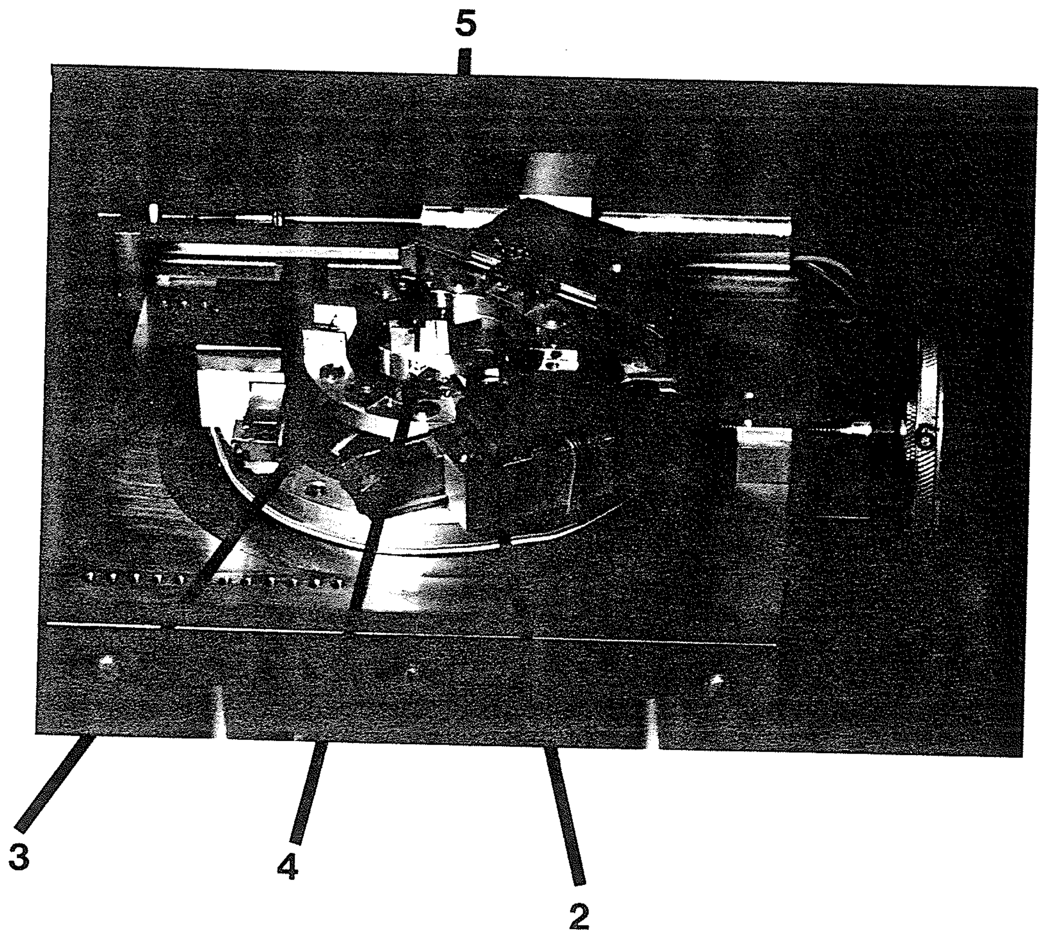
3.3.1 FORCE AND MOMENT DATA

The applied force system that each loop delivered to the molar to be uprighted was analyzed using the *in vitro* measuring system (see Figure 3) that was capable of measuring the applied forces and moments in three dimensions simultaneously.

The machine, developed by Paquien (1978) in which the duplicate loops were measured, consisted of four major parts: the frame; an internal suspended ring; a triangular block; and an electromagnetic vibrator. Six transducers, consisting of two types, were used in the measuring system to simultaneously measure the forces and moments in all three dimensions (Lack, 1980). The Type A transducers on the internal ring measured horizontal forces and pivoting moments. Type B transducers on the frame measured vertical forces and tipping moments. The maximum capacity of the transducers was 1300 grams of force and 23000 gram-millimeters of moment with normal full-scale being 1000 grams and 20000 gram-millimeters. The total error of the system was +/- 3% of full scale (or +/- 30 grams and +/- 600 gram-millimeters).

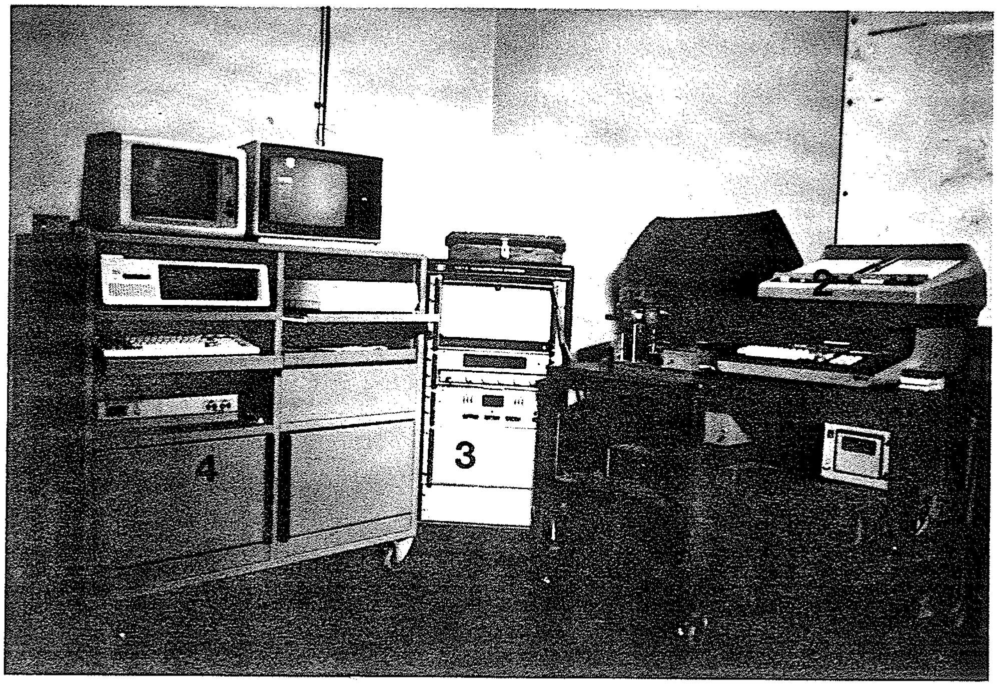
The measuring system was calibrated before final data accumulation to ensure the accuracy of the final force and moment results obtained from the in vivo-in vitro transfer.

This machine was linked to a Hewlett-Packard 9830A minicomputer (see Figure 4). This minicomputer was used to control the activation system, collect and store the data on magnetic tape, as well as to provide a check on the instrumentation. The Hewlett-Packard minicomputer was also interfaced with an X-Y Plotter, a tape-recording system and the Data Acquisition System (D.A.S.). The D.A.S. consisted of a 300 channel Hewlett-Packard cross bar scanner which allowed the information from each transducer to be collected in rapid sequence. For the purposes of easier manipulation of the raw data, the entire system was also linked to an I.B.M. minicomputer (see Figure 4) where the raw data was stored on floppy discs. The I.B.M. computer had a full range of data display and recording equipment which made it advantageous



1. Measured tooth.
2. Frame with Type B transducers.
3. Internal ring with Type A transducers.
4. Triangular block suspended on Type A transducers.
5. Linear voltage displacement transducer.
6. Mesio-distal adjustment screw.

Figure 3: The machine for measurement of force systems.



1. Machine for measuring force systems.
2. Hewlett-Packard minicomputer.
3. Data acquisition system.
4. I.B.M. minicomputer.

Figure 4: General view of the instrumentation.

to transfer data to this machine for final manipulation and storage.

Several computer programs were developed to support the experimental procedures. The programs consisted of:

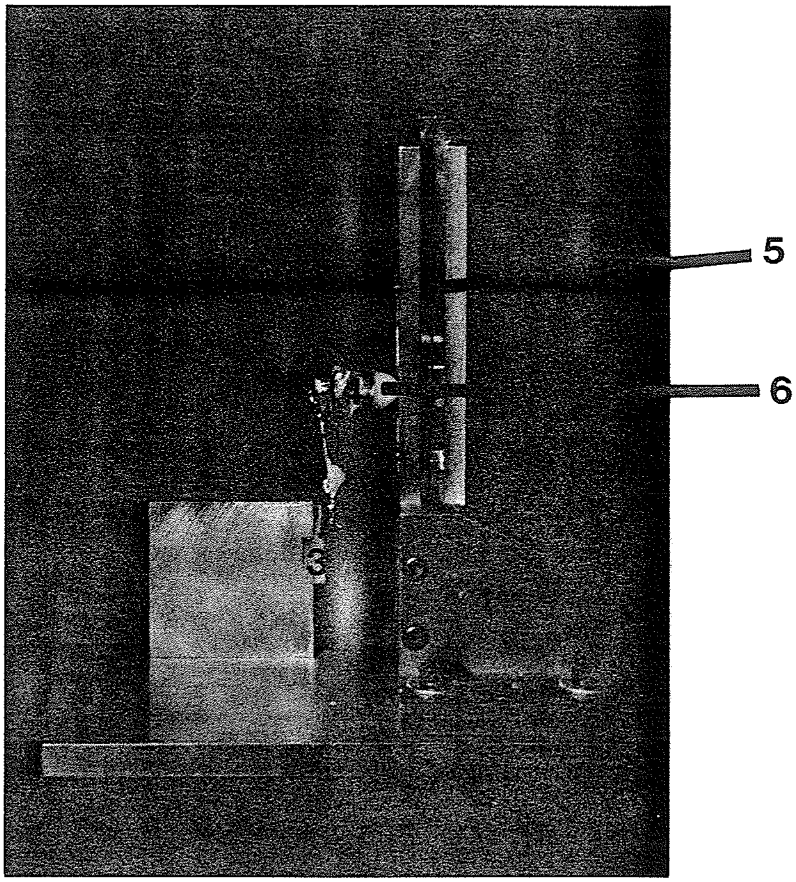
(1) two programs to provide procedural order to the collection of data on the forces and moments of loops;

(2) two programs which allowed the collected data from the Hewlett-Packard computer to be transferred to the I.B.M. computer;

(3) one program for the I.B.M. computer which allowed the centre of resistance of the measured tooth to be varied.

The passive template and the replica of the active loop used in the patient to upright the molar(s) were taken to the laboratory to be measured. A method for precisely transferring the findings *in vivo* to an *in vitro* condition on the machine was developed.

A brass gantry (see Figure 5) was built to enable the *in vivo* tooth positions to be duplicated for force measurements *in vitro*. For ease of manipulation of the passive template, the gantry was mounted in a base plate holder (also shown in Figure 5). The gantry consisted of two metal plates with two "windows." Between the two plates was a third plate that could be moved until it was



1. Brass Gantry.
2. Base plate.
3. "Active tooth" *in vitro*.
4. "Reactive tooth" *in vitro*.
5. Third metal plate (between two supporting metal plates) to allow mesio-distal and bucco-lingual adjustments.
6. Screw assembly.

Figure 5: Brass gantry.

in the correct mesio-distal and bucco-lingual position. It was then secured in that position by three screws (not shown in Figure 5). This third plate also held a screw assembly which, by virtue of its construction, allowed occluso-gingival as well as rotational adjustments to be made. This screw assembly consisted of the following:

a. A screw with a spherical end which allowed the correct occluso-gingival relationship of the "two-tooth" segment to be duplicated.

b. A spherical cap was made to fit over the spherical end of the screw. The concave surface of this cap was bonded onto the screw to allow the desired rotational adjustments to be made. The convex surface of this cap was machined to replicate the buccal surface of a bicuspid tooth.

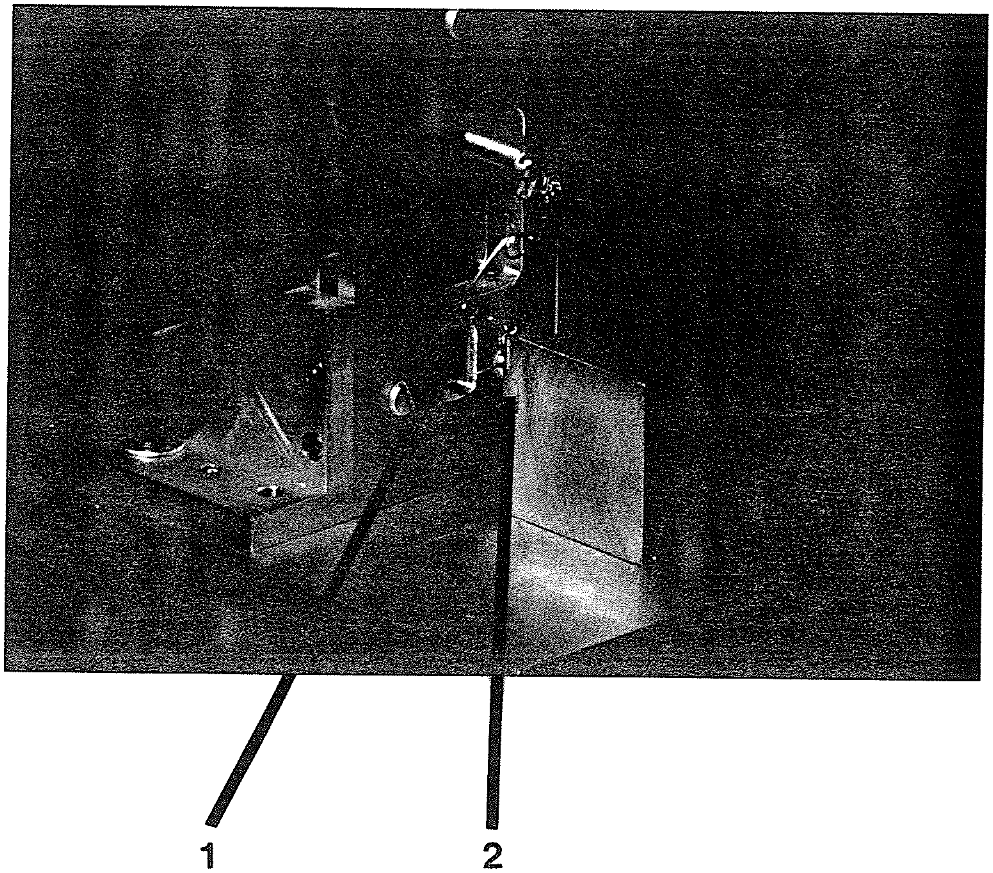
c. A Burstone bicuspid bracket with an 0.457 X 0.635 mm (0.018 X 0.025 inch) wire slot and an 0.559 X 0.711 mm (0.022 X 0.028 inch) tube (identical to that used in the clinical situation) was bonded onto the convex surface of the spherical cap. Now the "passive" template could be fixed in the exact *in vivo* bracket relationship using a similar force for ligation as that used in the patient.

In a similar manner, once the correct *in vivo* bracket relationship was obtained using the passive template, the active loop could be ligated into the brass gantry (see Figure 6). Figure 7 shows the active loop in the brass gantry now ready for transfer onto the machine. In order for this transfer to take place, the "molar tooth" had to be separated from the vertical holder. Once the gantry was secured onto the machine, the "molar tooth" was reattached to the measurement apparatus.

A rigid frame for the machine (see Figure 8) was made to hold the brass gantry. The gantry was then transferred onto the machine (see Figure 9) and attached to the rigid frame with four screws. In this manner, the force and moment data could be obtained for each appointment.

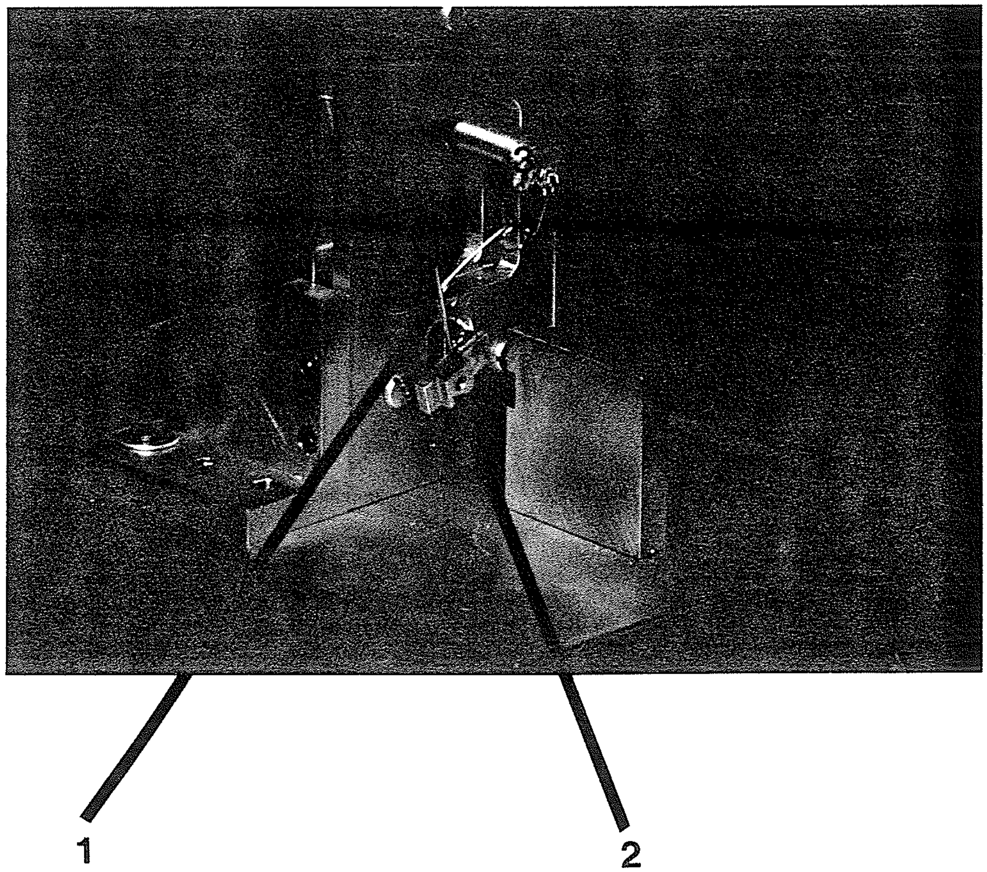
A preliminary force and moment reading was taken while the passive template was still in place in the respective brackets. This reading was the baseline (zero) reading from which the forces and moments of the active loop were measured. Now the passive template was removed and the active loop was ligated into the gantry. Ten consecutive readings were taken of the forces and moments acting on the measured (molar) tooth so that an average force and moment system could be calculated.

The force and moment data was collected using the



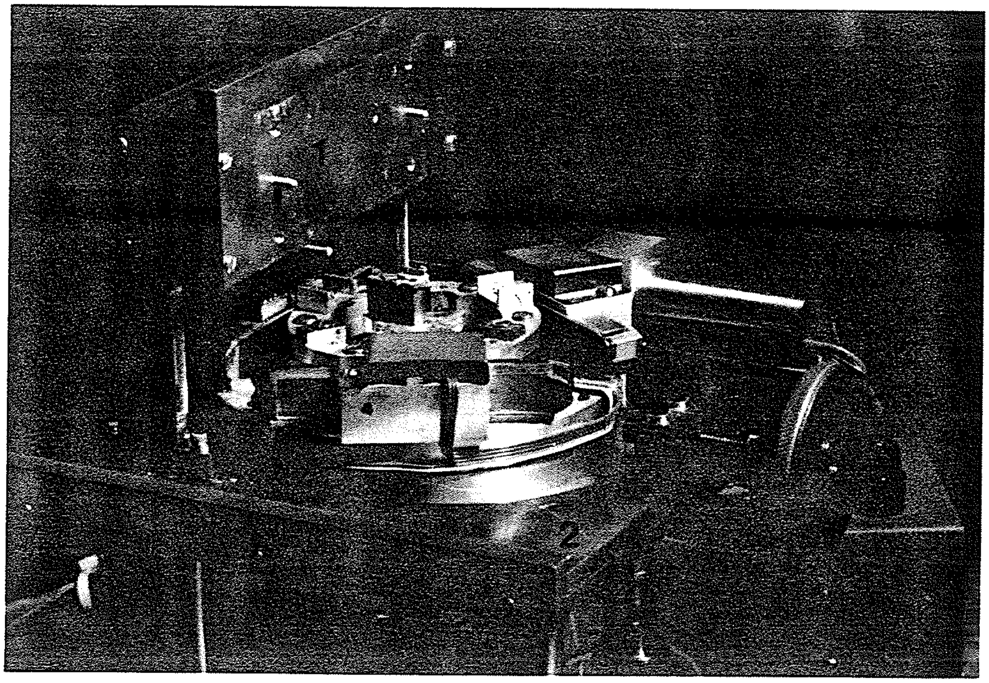
1. Active loop ligated into brass gantry.
2. "Active tooth" in vitro.
3. "Reactive tooth" in vitro.
4. Brass gantry mounted in vertical holder.

Figure 6: Active loop ligated into brackets in brass gantry.



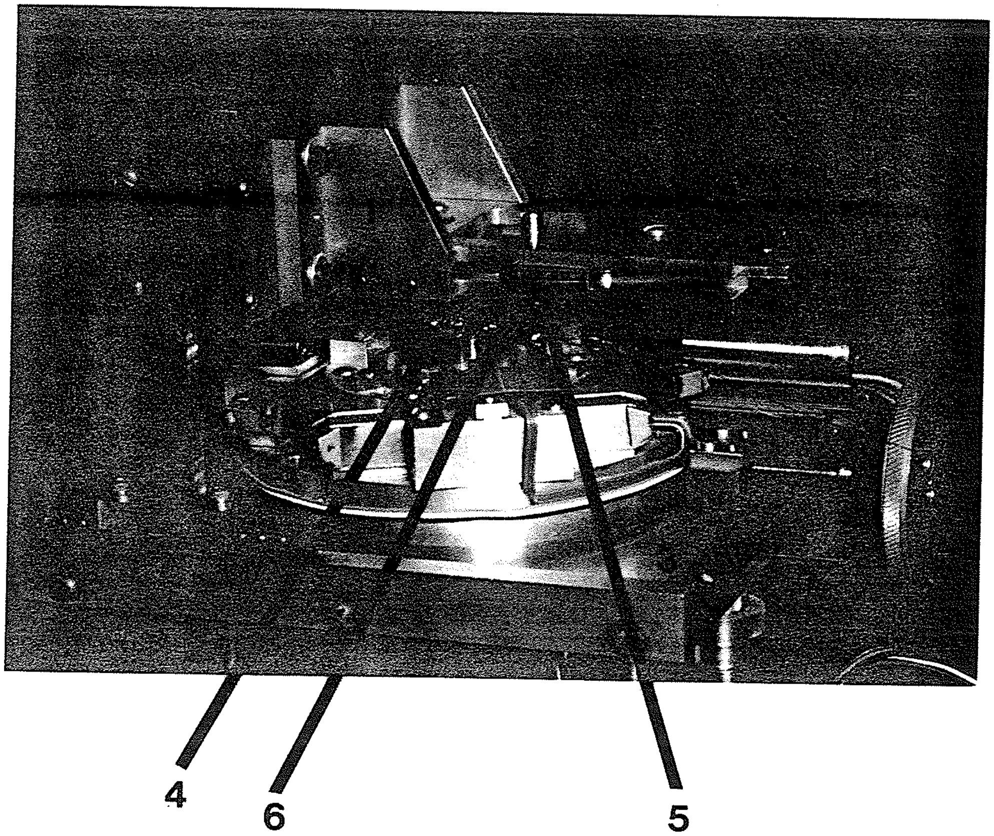
1. Active loop unscrewed from "active tooth" to enable brass gantry to be transferred onto machine for force system measurement.
2. "Active tooth" _in vitro_.
3. "Reactive tooth" _in vitro_.

Figure 7: Active loop ready for transfer onto machine.



1. Rigid frame to support brass gantry.
2. Machine.

Figure 8: Rigid Frame on machine to support brass gantry.



1. Brass gantry.
2. Rigid frame to support brass gantry.
3. Machine.
4. Measured tooth: _in vitro_ molar requiring uprighting.
5. Screw assembly holding "reactive tooth".
6. Active loop to be measured.

Figure 9: Brass gantry on machine.

machine axis system. However, for ease of presentation, this data was converted so that a conventional axis system (Figure 10) could be shown. Thus, the forces and moments will be referred to as follows:

(1) force in the x direction (Fx): force in the mesio-distal direction;

(2) force in the y direction (Fy): force in the occluso-gingival direction;

(3) force in the z direction (Fz): force in the bucco-lingual direction;

(4) moment about the x axis (Mx): rotation around the mesio-distal axis (which is bucco-lingual tipping);

(5) moment about the y axis (My): rotation around the occluso-gingival axis (which is mesio-lingual, mesio-buccal, disto-lingual or disto-buccal tipping);

(6) moment about the z axis (Mz): rotation around the bucco-lingual axis (which are mesial or distal (ie. uprighting) rotations).

3.3.2 TOOTH MOVEMENT DATA

An accurate technique for measuring tooth movement in three dimensions was mandatory in order to provide the necessary data on tooth position and angulation changes. Therefore, a sufficient number of points had to be

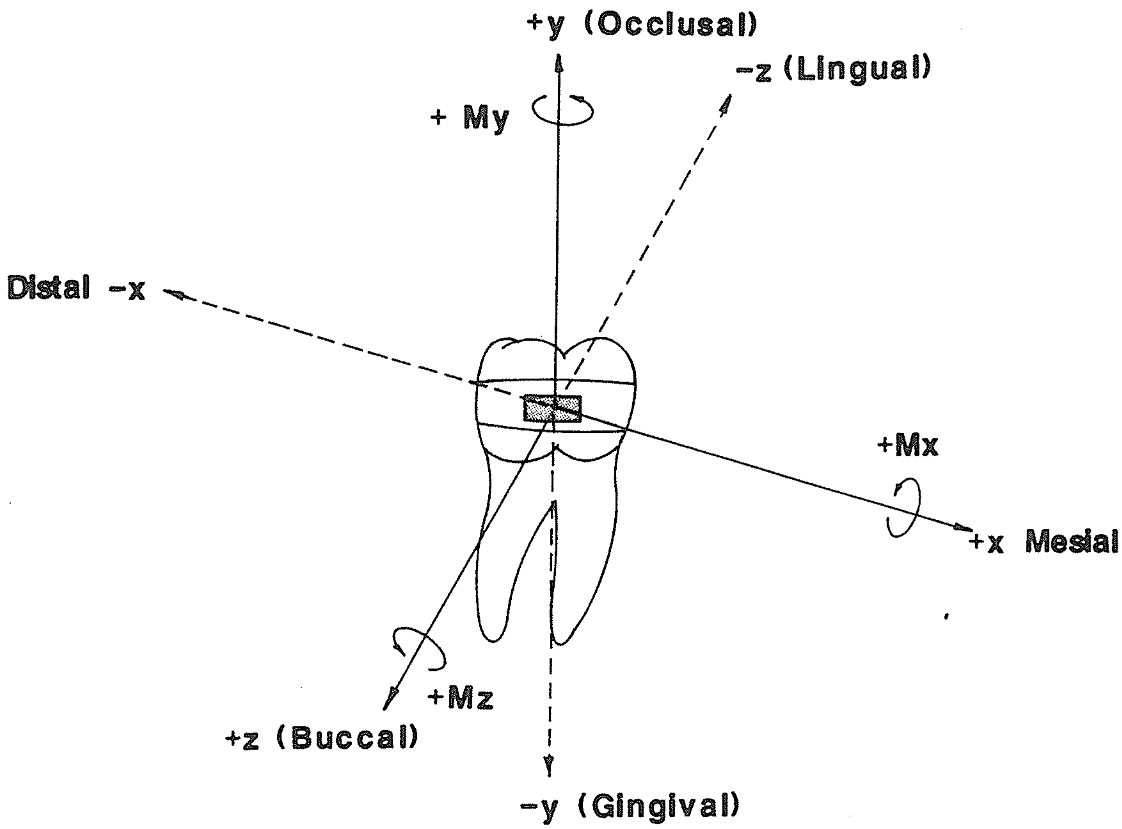
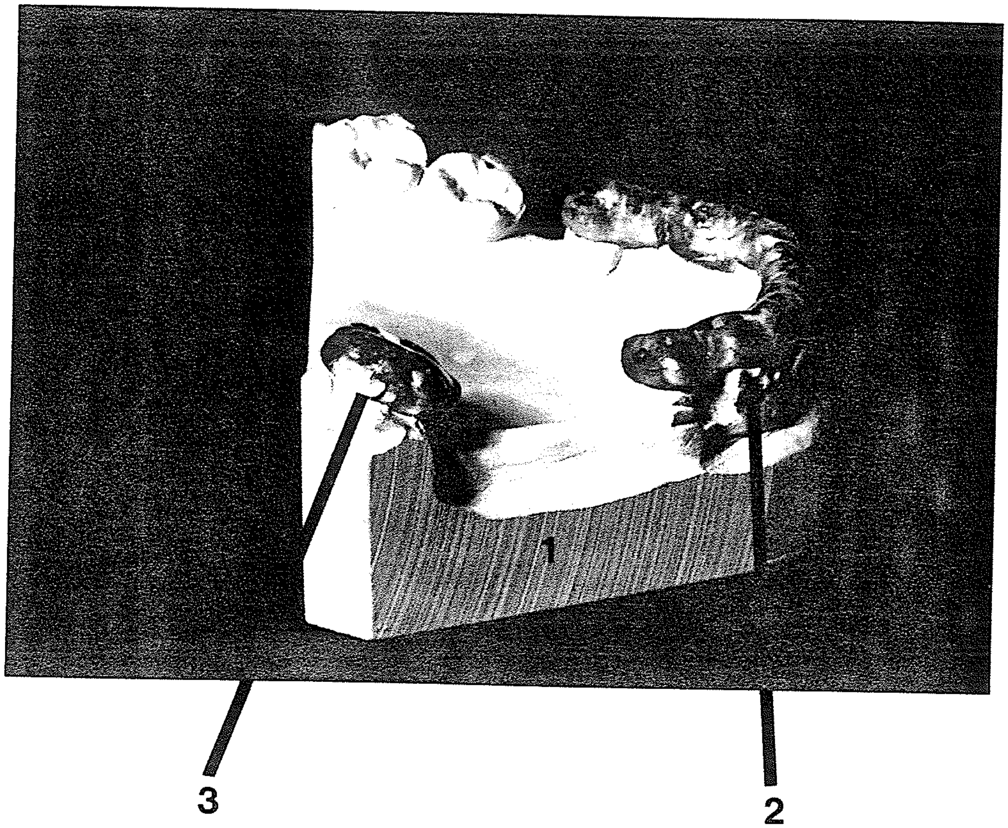


Figure 10: Axis system used to describe force systems.

repeatably and precisely identified and measured so that longitudinal data concerning the three translational and three rotational movements could be derived both for the active and reactive teeth. At present, no satisfactory technique exists whereby tooth position changes can be measured intra-orally. Therefore, an in vitro technique using study casts taken at each appointment was developed.

Before any measurements could be made, a sufficient number of points had to be repeatably and precisely identified. To achieve precision of landmark identification, a technique for replication of landmarks from cast to cast was developed. Acrylic templates (3 mm acrylic sheets, Biostar Pressure Molding Machine) were made as described in section 3.2.2. Each template was divided so that the anchor segment and molar(s) segments were separate (see Figure 11). Accurate fit of the anchor segment template was taken as one piece of evidence of the stability of the anchor segment. Other checks on the stability of the anchorage unit included relating differences in measurements between teeth to the different casts. These were found to be very constant. A third method was to compare the individual points measured in the anchorage unit to the calculated reference axes. The data for these distances is found in Appendix C. A fourth



1. Study cast to be measured.
2. Anchorage segment with acrylic template.
3. Molar requiring uprighting with acrylic template.

Figure 11: Study cast with acrylic template.

method of checking the stability of the anchorage segment was the superimposition of occlusograms taken by an Unitek Orthoscan Camera.

Holes were drilled into the templates as follows:

-each bicuspid, whether the reactive bicuspid or not, had 3 or 4 holes (depending on the size of the bicuspid) drilled through the occlusal surface of the template to allow precise marking of buccal, lingual, mesial and/or distal aspects of the tooth;

-each cuspid had one hole drilled for marking the cusp tip;

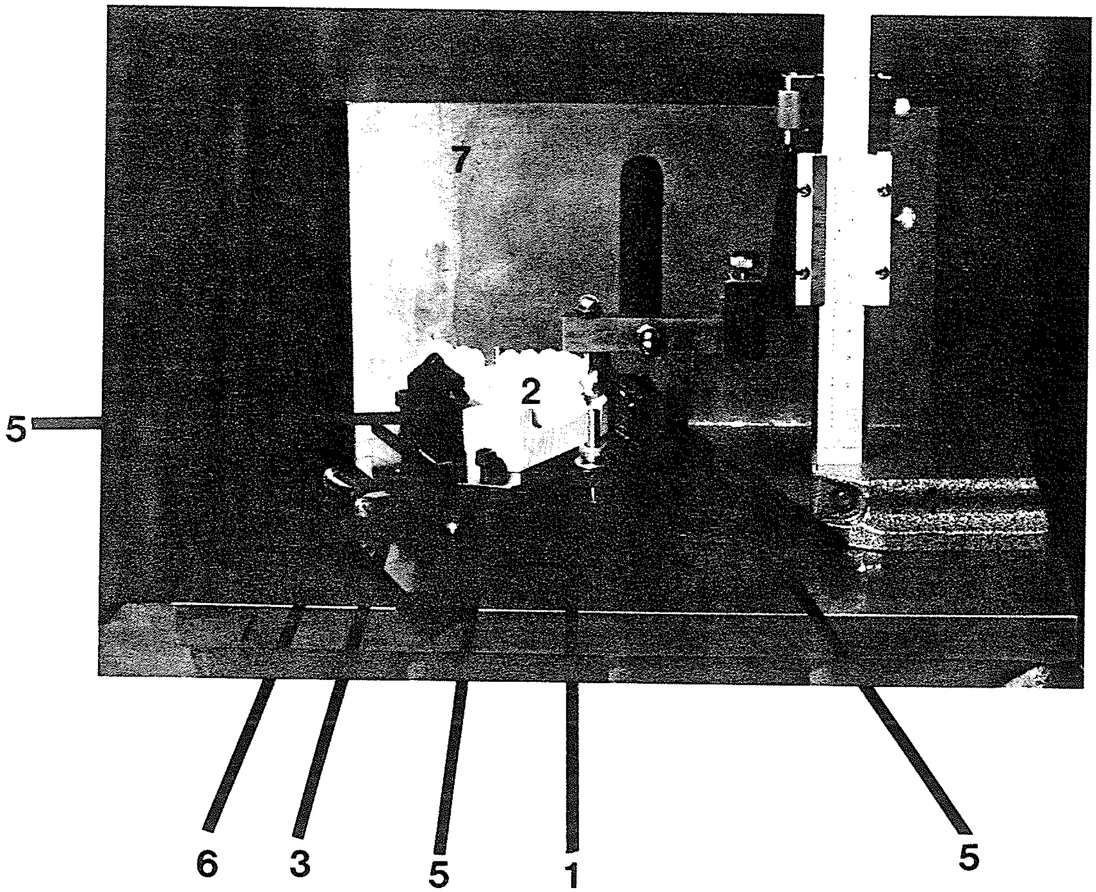
-each central incisor had one or two holes drilled onto the incisal edges;

-each molar had 4 holes drilled, one each for the four cusp tips. It was felt that, use of the cusp tips of the molar provided easily identifiable landmarks so that visual comparisons between casts could be made as well. Also, the distances between the four points was maximized so that rotational movements of the molar could be calculated with sufficient accuracy.

In this manner sufficient landmarks were precisely identified to enable accurate measurement of changes in tooth position.

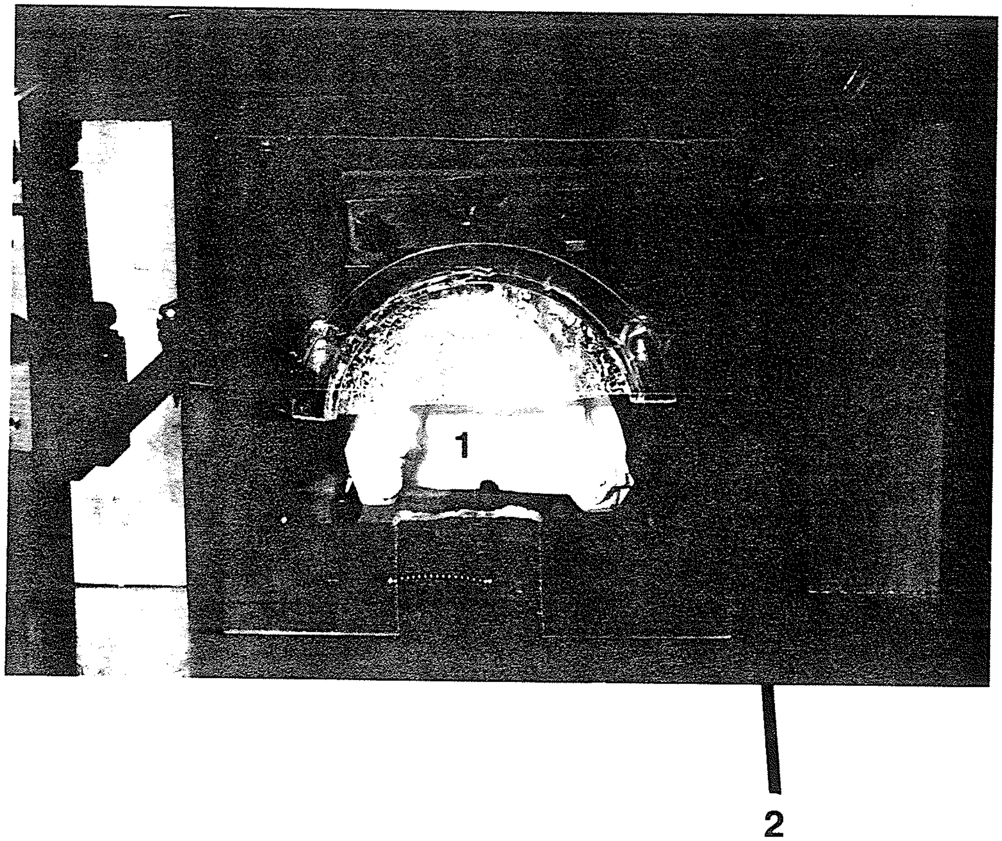
Once the landmarks on the casts were marked using the templates and a lead pencil the casts were ready to be measured. A measurement apparatus was developed that allowed adjustments to be made in all three dimensions (see Figure 12). By precise measurement of the previously described landmarks relative to the three orthogonal axes of the measurement apparatus, comparisons in the observed tooth movement as the molar was uprighted could be made.

The cast was secured onto a metal plate that had three screws which allowed the plate to be adjusted in the occluso-gingival direction and rotationally around the antero-posterior and medio-lateral axes. This plate was mounted onto another precisely machined metal plate which had the edges at 90 degrees to one another (see Figure 12). Measurements in the occluso-gingival direction direction were made with the plaster cast base parallel to the floor (see Figure 12) using a Vernier Height Gauge with an accuracy of 1/100th millimeters. Because the Vernier Height Gauge only measures in the vertical direction, measurements in the other dimensions had to be made by moving the measurement apparatus. Thus, measurements in the mesio-distal direction were made by standing the plate on its side (see Figure 13) with the posterior base of the plaster cast inferior. Measurements in the bucco-lingual



1. Measurement apparatus.
2. Study cast in position ready for occluso-gingival measurements.
3. Screw to secure cast.
4. Vernier height gauge.
5. Screws for occluso-gingival adjustments.
6. Screw for rotational adjustments.
7. Large, precisely machined table to support measuring apparatus.

Figure 12: Measuring apparatus.



1. Study cast to be measured.

2. Measurement apparatus on its side with posterior surface of cast facing inferiorly.

3. Acrylic template with horizontal line parallel to measurement apparatus base.

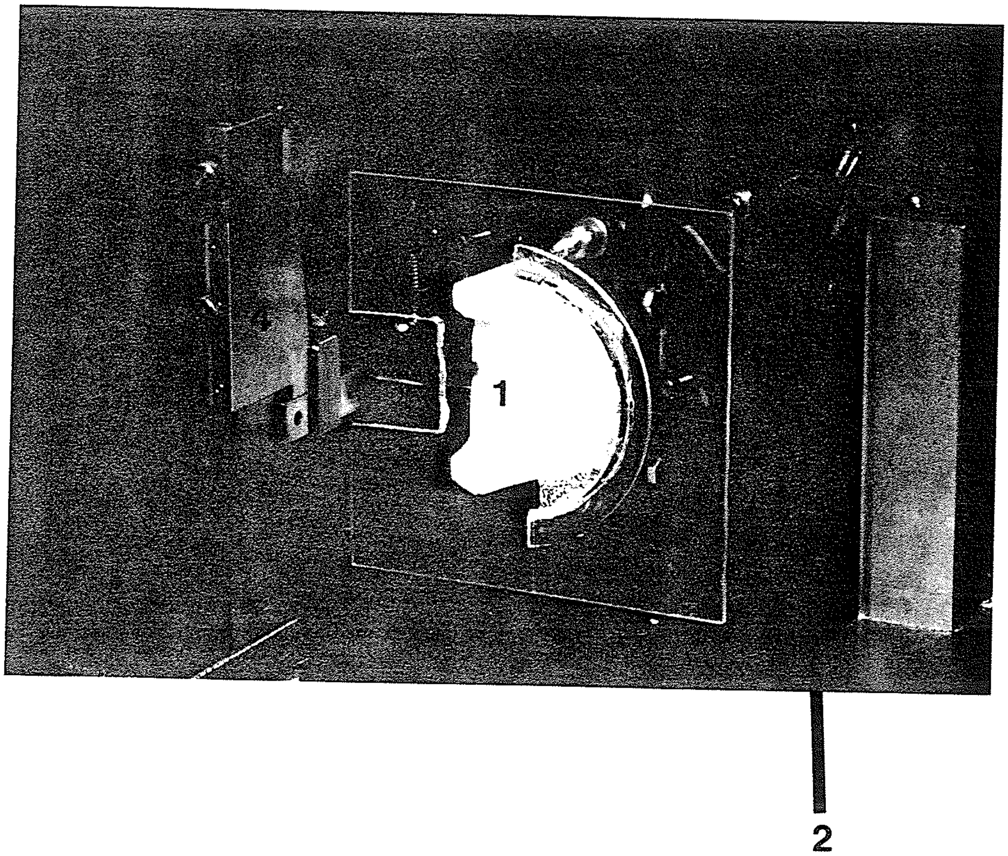
4. Vernier height gauge.

Figure 13: Measurement apparatus showing cast ready for mesio-distal measurement.

direction were made by turning the plate 90 degrees (see Figure 14).

In order to facilitate the initial placement of the casts, another acrylic template was made to to fit over the occlusal surfaces of the anchor segments (see Figures 13 and 14). This template was then glued onto a 3mm thick acrylic square with perpendicular lines scribed onto its surface. When this combination template was placed over the occlusal surfaces of the anchor segment, the position of the scribed lines enabled a quick estimate of the cast orientation to be made. The horizontal line was then adjusted so that it was exactly parallel to the base of the third metal plate. A final orientation adjustment was made after removing this combination template and checking the distance between three selected reference points on the teeth in the anchor segment.

A preliminary test was undertaken to determine the accuracy of locating a single point as well as to determine the accuracy of measurements between casts, the details of which are given in Appendix B. The accuracy was 0.11 millimeters.



1. Study cast to be measured.
2. Measurement apparatus on its side with posterior surface of cast perpendicular to floor.
3. Acrylic template with horizontal line parallel to measurement apparatus base.
4. Vernier height gauge.

Figure 14: Measurement apparatus showing cast ready for bucco-lingual measurements.

3.4 DATA ANALYSIS

3.4.1 FORCE AND MOMENT DATA

The force and moment magnitude and tooth position change had to be organized into a form that allowed interpretation.

The data for the measured forces and moments in all three dimensions (ie. Fx, Fy, Fz, Mx, My, and Mz) was obtained for each appointment. Each active appliance was measured ten times and the results were then averaged. These results were graphed to facilitate interpretation as well as to make it easier to compare the tooth movement to the measured force system.

3.4.2. TOOTH MOVEMENT DATA

The data from cast measurement was analyzed as follows:

(1) The point of origin for the mesio-distal (x), occluso-gingival (y) and bucco-lingual (z) reference axes was determined by averaging all of the reference points as measured in the three dimensions respectively on the anchor segment. This point will be referred to as the reference point.

(2) Measurements were made to verify anchor segment stability. This technique involved referring the

measured teeth in the anchor unit to the reference point described above. Obviously, the relative distances of these teeth in the anchor segment as measured to the reference point would not vary greatly from cast to cast if the anchor unit remained stable.

(3) The degrees of uprighting of the molars were calculated using the following formula:

$$\text{Degrees of Molar Uprighting} = \text{inverse sine}\left[\frac{\left[\dfrac{(MB - DB)}{MB \text{ to } DB} + \dfrac{(ML - DL)}{ML \text{ to } DL}\right]}{2}\right]$$

where (MB - DB) and (ML - DL) referred to measured differences in these cusp heights in the occluso-gingival dimension.

and MB to DB and ML to DL referred to the absolute distance between these cusps regardless of the axis.

Because the distances between these points was small, a measurement error of 0.10 millimeters on each point could produce a maximum error of approximately 2.5 degrees in the calculated angle of uprighting.

(4) To measure the mesio-distal linear movement of the crown of the uprighting molar, a single point on the molar crown was defined for each axis by averaging the four values obtained for each cusp on the molar in each dimension. This value was then measured to the reference axis. As this distance increased, the crown

of the molar moved distally. The resulting distal crown movement was also compared to superimpositions of occlusograms of successive casts to verify measurements.

(5) The other linear molar movements in the occluso-gingival and bucco-lingual directions were made using an average (calculated using the four points marked on the occlusal surface of the molar) value for the molar crown and comparing how this value changed in relation to their respective axes.

(6) The mesio-distal and bucco-lingual rotations were measured in two ways. The first method used a calculated method similar to that described in #3 above. However, because of the changing relationship of the occlusal surface of the molar to the reference axes, which would increase these rotational angles calculated, another method using direct measurements from the casts was done. This second method involved fixing wires onto the occlusal surfaces of the acrylic templates. The wire on the anchorage segment was the reference as this segment position from cast to cast did not change. Thus, mesio-distal or bucco-lingual changes in molar position in the mesio-distal or bucco-lingual were reflected in a change in the

relationship of the wire on the occlusal surface of the molar template compared to this reference wire. A protractor was used to measure these changes. Mesio-distal rotations were also checked using the occlusograms.

(7) The molar movement was then graphed to facilitate interpretation.

CHAPTER IV

RESULTS AND DISCUSSION

RESULTS AND DISCUSSION

The purpose of this investigation was to develop a technique whereby accurate three-dimensional information of tooth movement and applied force systems could be obtained. A three-dimensional cast measurement apparatus was developed to enable tooth movement to be recorded in three dimensions. The force systems were measured in three dimensions simultaneously using instrumentation previously developed at the University of Manitoba.

Initially, five patients were selected for this study. However, the data from one patient were made suspect by the loss of a splint on three occasions and therefore, occlusal forces could have interfered with the resulting tooth movement and applied forces. Another patient, requiring orthognathic surgery, could not be completed because of surgical time constraints. Thus, the results from a total of three patients and four molars will be reported. One of these patients (NL) had bilateral lower second molars requiring uprighting.

In developing a technique, it is difficult not to use it as well. Thus, the results obtained have to be discussed in several different ways. The first is that of relating the observed molar uprighting tooth movement to the applied force systems. As only four molars were used, no definitive, general conclusions regarding tooth movement could be made but trends will be reported. The second and most important manner of discussing the results was to determine if the results obtained supported use of this technique as a means of quantifying tooth movement in response to known applied force systems. The third manner was to introduce the capabilities of this technique in relating force systems to estimated centres of resistance of teeth.

4.1 MOLAR UPRIGHTING RESULTS

4.1.1 DATA PRESENTATION

To allow superficial comparision of molar uprighting, results for the four molars will be shown on one graph. It is emphasized again that, with so few teeth, general conclusions regarding patterns of tooth movement in relation to applied force systems cannot be made. The purpose of combining the data of the four molars on one graph for each of the three linear and three rotational movements was to indicate trends between the four molars.

The molars will be referred to by the patient's initials and their tooth number (using the International numbering system).

The three linear and three rotational movements and their corresponding measured applied forces and moments are shown in graphical form to facilitate interpretation. The data was collected at as regular time intervals as possible. The decision to discontinue the uprighting was made on a basis of clinical judgement in each case. Thus, it was not surprising that some variation existed from case to case in the final angulation of the molar with respect to the reference axes.

The linear position results were obtained by measuring four points on the occlusal surface of the molar to be uprighted and then averaging these four values. This average value will be used for each clinical situation to describe the obtained linear tooth position. These data were then graphed to show tooth position with respect to time (ie. from appointment to appointment). The data points are connected by straight lines to indicate their temporal relationship but they do not, of course, represent the path of the tooth from position to position nor its path to its final destination.

The force systems applied to the molar to be uprighted were measured at the bracket for each activation of the appliance. These results are also graphed for easier interpretation.

4.1.2 REFERENCE AXES

The data for tooth position changes that occurred in the anchorage unit are presented in Appendix C. The reported values represented the distances of the points marked on the anchorage unit to the calculated reference axes in millimeters. Examination of these results showed that there was very little movement within the anchorage unit as the values generally only varied by +/- 0.1 mm (the measurement error calculated in Appendix B) from cast to cast. Occlusograms taken of the casts at each appointment and superimposed for best fit of all the points on the anchor segment showed that movement of the entire anchorage segment was clinically insignificant as the points superimposed well. It was because of the relative stability of the teeth within the anchor segment as well as the relative stability of the anchorage segment as a whole as measured from cast to cast that meaningful tooth movement data, namely molar uprighting, could be obtained.

4.1.3 GRAPH INTERPRETATION

A. LINEAR MOVEMENTS (graphed in millimeters):

i. Distal crown movement is represented by a negative slope;

ii. Gingival crown movement is represented by a negative slope;

iii. Lingual crown movement is represented by a negative slope.

B. ROTATIONAL MOVEMENTS (graphed in degrees):

i. The degree of mesial tip of the molars was measured to a line parallel to the reference occluso-gingival axis. Thus, any uprighting of the molar would be reflected in a decreasing measured angle of uprighting.

ii. Disto-lingual rotation of the crown was represented by a positive slope.

iii. Buccal crown tipping, about the mesio-distal axis, was represented by a positive slope.

The following legend was used for the force and moment data on the graphs:

C. APPLIED FORCES (grams):

i. Positive mesio-distal forces represent a mesially directed force;

ii. Positive occluso-gingival forces represent an extrusive force;

iii. Postive bucco-lingual forces represent a buccally directed force;

D. APPLIED MOMENTS (gram-millimeters):

i. Distal molar tipping, about the bucco-lingual axis, is represented by positive moments.

ii. Disto-lingual molar rotation about the occluso-gingival axis is represented by a positive moment.

iii. Buccal tipping of the molar about the mesio-distal axis is represented by positive moments.

4.1.4 MOLAR UPRIGHTING

Figure 15 shows the degrees of uprighting achieved for each of the four molars. It may be seen that in all cases, the primary objective of molar uprighting was achieved although the absolute amount of uprighting varied from patient to patient.

Figure 16 shows the applied uprighting moment at the bracket for each of the molars. This uprighting moment varied according to the amount of activation placed into the loop and was also dependent on the amount of wire incorporated into the loop (which influenced the stiffness

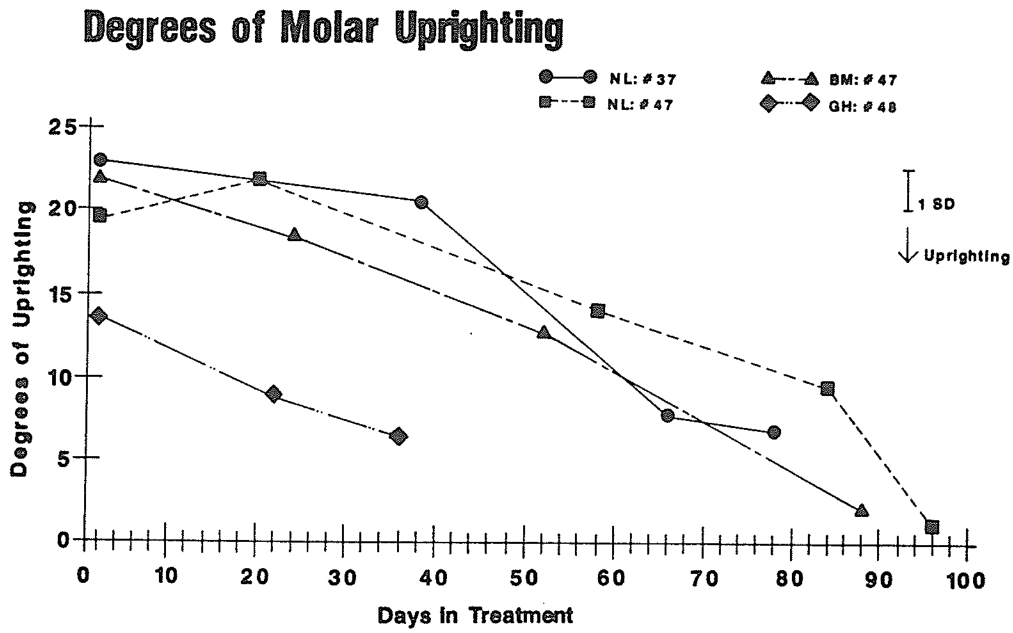


Figure 15

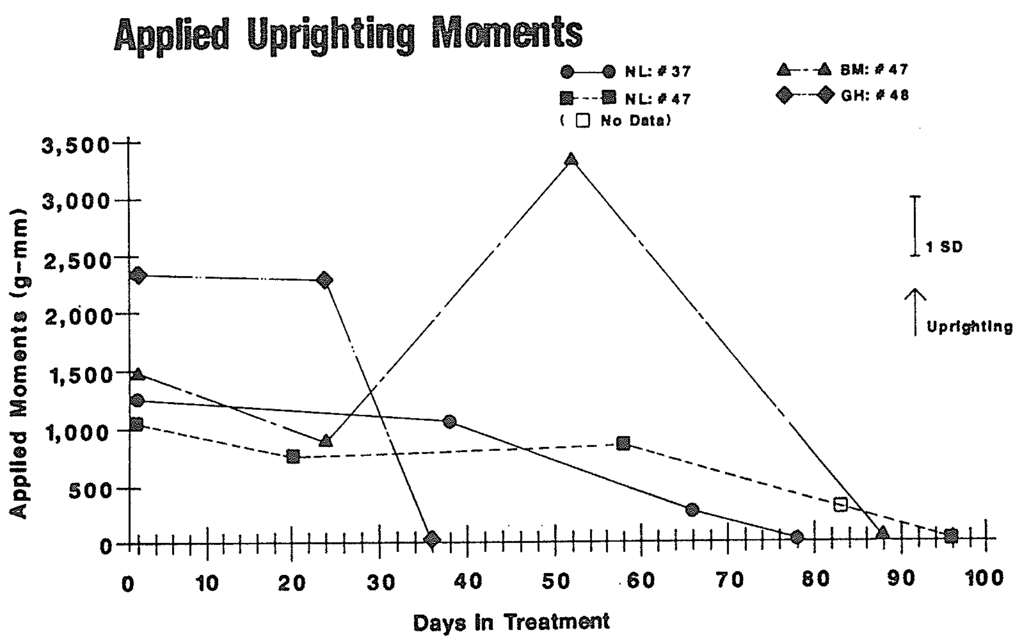


Figure 16

of the loop and thus, the constancy of moment delivered) and the type of loop used. The interbracket distance between the molar to be uprighted and the bicuspid tooth varied from seven millimeters (in patient BM(#47)) to twenty-five millimeters (in patient GH(#48). Thus, the amount of wire needed to make an uprighting loop for the clinical situations varied greatly. Using Navier's equation, a two-fold increase in wire incorporated into an appliance would decrease the stiffness of the appliance by a factor of eight (Thurow, 1982).

Another variable was the fact that the molar uprighted was not always the lower second molar. Root configurations of lower third molars are known to vary a great deal often being more conical in shape than lower second molars. Thus, an applied force system would tend to give rise to a different movement response depending on the type of tooth being uprighted.

Variable root configurations as well as variations in surrounding alveolar bone would influence the centre of resistances of teeth which in turn, would influence the response of the teeth to the applied force system. As mentioned previously, using values from the force systems measured at the brackets removed the effect of differing centres of resistance. Thus, the force systems applied by the loops used were being measured. Section 4.3 will show how the force system changed when measured at an estimated centre of resistance for one of the molars (BM(#47)) used in this investigation.

For patient NL(#37), a T-Loop was used to upright the lower left second molar (#37). A total of sixteen degrees of uprighting was achieved in four appointments over a total of 78 treatment days (see Figure 15). Forty-five degrees of activation were placed into each end of the uprighting loop at the first two appointments. This activation gave a relatively constant moment delivery of slightly over 1000 g-mm. At the third appointment, the molar was considered almost upright. Therefore, only thirty degrees of activation was placed into the appliance. This yielded a smaller uprighting moment as seen in Figure 16. It was also interesting to note that the path of molar uprighting using the T-Loop seemed to be the most variable. The slopes of the lines connecting tooth position at the various appointments varied greatly as can be seen on Figure 15.

For patient NL(#47), a BUS was used to upright the lower right second molar (#47). A total of 18.5 degrees of uprighting was achieved in five appointments over a total of 96 treatment days (see Figure 15). Forty-five degrees of activation was placed into the appliance at both ends at the first three appointments. This yielded a similar moment delivery of around 1000 g-mm as for NL(#37) (Figure 16). Unfortunately, the passive template for the fourth appointment broke. Thus, no value for the force systems could be obtained for this appointment. However, at this appointment, the molar was also considered to be relatively upright and thus, only 30 degrees of activation was placed into the BUS.

For patient BM(#47), a BUS was used to upright the lower right second molar (#47). A total of 19 degrees of uprighting was achieved in four appointments over a total of 88 treatment days (see Figure 15). Because of the small initial interbracket distance between the molar and the reactive tooth, an initial activation of thirty-five degrees was placed into the appliance. This amount of activation gave approximately the same uprighting moment as the forty-five degree activations placed into patient NL above (see Figure 16). Forty-five degrees of activation for patient BM(#47) was found to be too difficult to ligate into the teeth and thus, was felt to probably deliver too great an activation as well. At the second appointment, the molar was slightly sore, so the activation applied to the uprighting appliance was decreased to thirty degrees. This gave a smaller applied uprighting moment. At the third appointment, the molar was no longer sore. Also, the interbracket distance had increased due to distal crown movement. Thus, a forty-five degree activation was placed into the appliance. This gave a significantly higher uprighting moment as seen in Figure 16.

For patient GH(#48), a BUS was used to upright the lower right third molar (#48). A total of 7 degrees of uprighting was achieved over a total treatment time of 35 days (see Figure 15). Forty-five degrees of activation was placed into this appliance at both appointments. A similar uprighting moment slightly greater than 2000 g-mm was measured for these activations (see Figure 16).

It was interesting to note that, when the degrees of uprighting for each molar was averaged over the days in treatment, approximately 0.2 degrees/day or 6 degrees/month of uprighting was achieved in each situation. Thus, the rate of uprighting seemed to be independent of the applied moments over the range of values used in this investigation. Also, patients BM(#47) and GH(#48) were female and were eight years older than patient NL (#37 and #47) who was male. The averages of the applied uprighting moment for patients BM(#47) and

GH(#48) were twice that measured as the uprighting moment for patient NL(#37 and #47). In spite of this difference in measured applied uprighting moment, the molars seemed to upright at approximately the same average rate.

Perhaps these results are a reflection of the effects of a combination of several variables including sex, age (implying differences in alveolar bone structure and availability of osteoclastic/osteoblastic cells) and the type of tooth movement studied. Tipping movements, such as molar uprighting, introduce several variables which mask study of the relationship between force and rate of tooth movement (Hixon et al, 1970). "Besides the initial compression of the periodontal ligament, the most obvious variable is the unequal distribution of the load along the root. The high load at the alveolar crest, which decreases to zero at the axis of rotation, is also capable of deforming the wall of the socket. The magnitude of such bone bending may also be sufficient to influence interpretation of the data utilized for studying tooth movement." Buck and Church (1972), using data from human subjects, suggested that even light tipping forces on teeth resulted in extreme compression of the periodontal ligament with ischaemia and loss of cellular elements. Thus, perhaps even the lowest applied uprighting moment exceeded the optimal value for uprighting. Molar uprighting initially concentrated the stresses in very small areas at the apex and opposite coronal alveolar bone which could very quickly make the force levels felt in these areas very high. Once the optimum force system for a particular tooth movement is exceeded, perhaps no increase in rate of tooth movement would be observed (Quinn and Yoshikawa, 1985).

4.1.5 LINEAR TOOTH POSITION

A. MESIO-DISTAL POSITION

In all cases, the crown of the molar moved distally as the molar uprighted (see Figure 17). The amount of distal movement varied with the amount of uprighting and ranged from 1.5 mm (in patient GH(#48)) to approximately 6 mm (in patient BM(#47)). Again, the most variable path of distal crown movement seemed to occur with the T-Loop as seen with patient NL(#37).

The mesio-distal forces measured (see Figure 18) indicated that an initial mesially directed force, with magnitudes varying between 10 and 120 grams, were felt at the bracket. This was interesting as in no case did the crown move mesially. Only in one case, at the first appointment for NL(#47), was an initial large distally

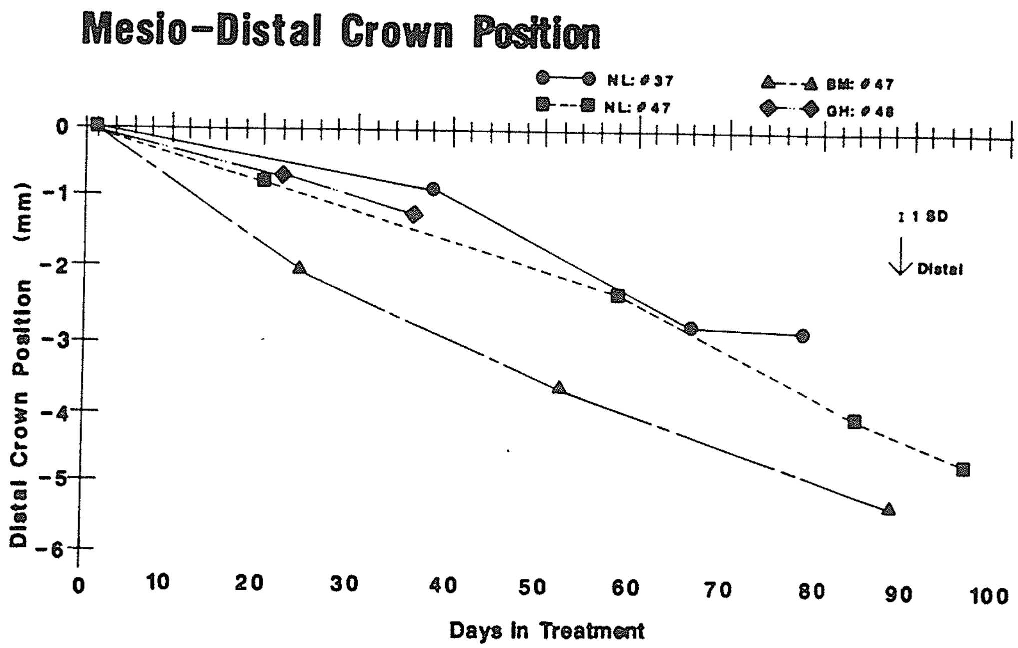


Figure 17

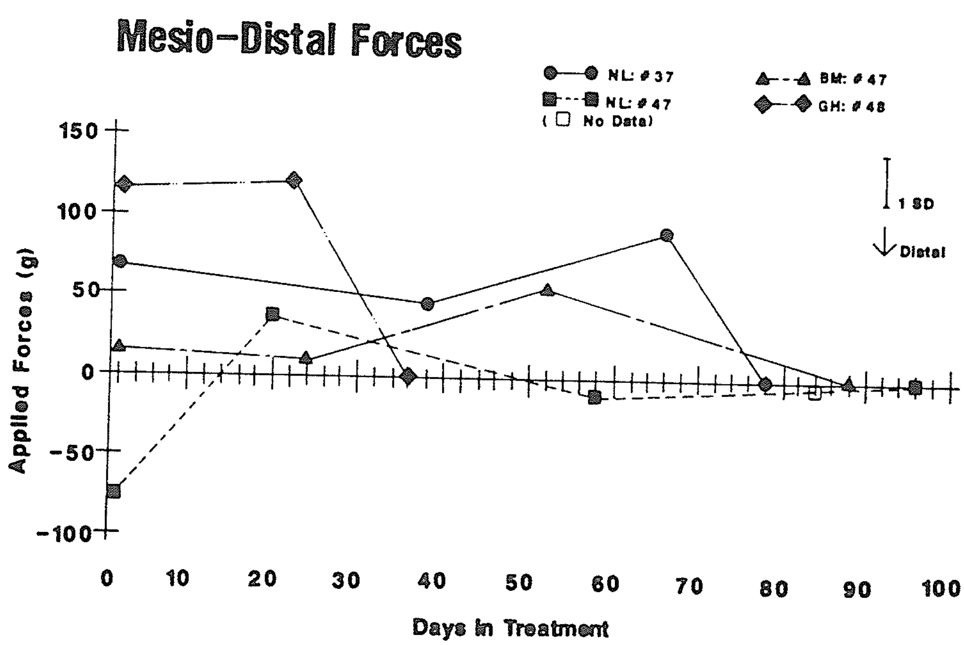


Figure 18

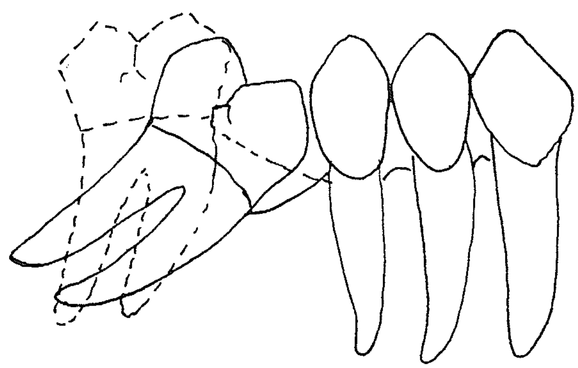
directed force of approximately 75 grams measured at the bracket. This measured distally directed force did not influence the rate of distal crown movement as the slope of the line between appointments one and two on Figure 17 for NL(#47) show that approximately the same rate of distal crown movement was achieved as for patient GH(#48). At the third appointment for patient NL(#47), again a distally directed force was observed but of a very small magnitude (5 grams) well within the error range of the machine. Thus, it was possible that actually a mesially directed force might have been felt.

Examination of the technique of ligation of these appliances into the patient's mouth revealed that a very subtle opening of the vertical legs of the appliances occurred as the appliance was tied into the respective brackets. This would account for the initial mesially directed force measured. However, as the uprighting of the molar occurred, and with the jiggling forces of occlusion, this force could be expected to dissipate quickly allowing only the uprighting moment to be felt. Also, in all cases, the uprighting moment was large enough to overcome the measured mesial forces.

B. OCCLUSO-GINGIVAL POSITION

Uprighting a mesially tipped molar causes the crown of the molar to move in an occlusal direction even if the centre of resistance of the tooth does not change its position occluso-gingivally (see Figure 19). Roberts et al (1982) refer to this as "false" extrusion and describe it as the result of the eruption, or extrusion which occurred during the time the molar tipped into the extraction space. "True" extrusion of the molar, where the centre of resistance actually moves in an occlusal direction, might be due to the anatomy of the molar, periodontal ligament and surrounding alveolar socket. Graber (1972) said that, to depress a tooth, extremely strong forces are required sufficient to tear the fibers loose from their attachments and exert pressure on the alveolar walls and apex. In addition, just as the shape of the molar roots is similar to that of all other teeth in that the roots tend to taper apically, it is easier for the tooth to move along the inclined plane formed as a result of this taper than to intrude. Also, all of the natural tissue responses are working with this tooth movement as the tooth is moving in the direction of normal physiological eruption (Thurow, 1962).

In patient NL(#37), where a T-loop was used, slightly over two millimeters of average occlusal movement of the crown was observed (see Figure 20). As mentioned



Extrusion results from correction of molar inclination by pure rotation.

Figure 19 (from Roberts et al, 1982)

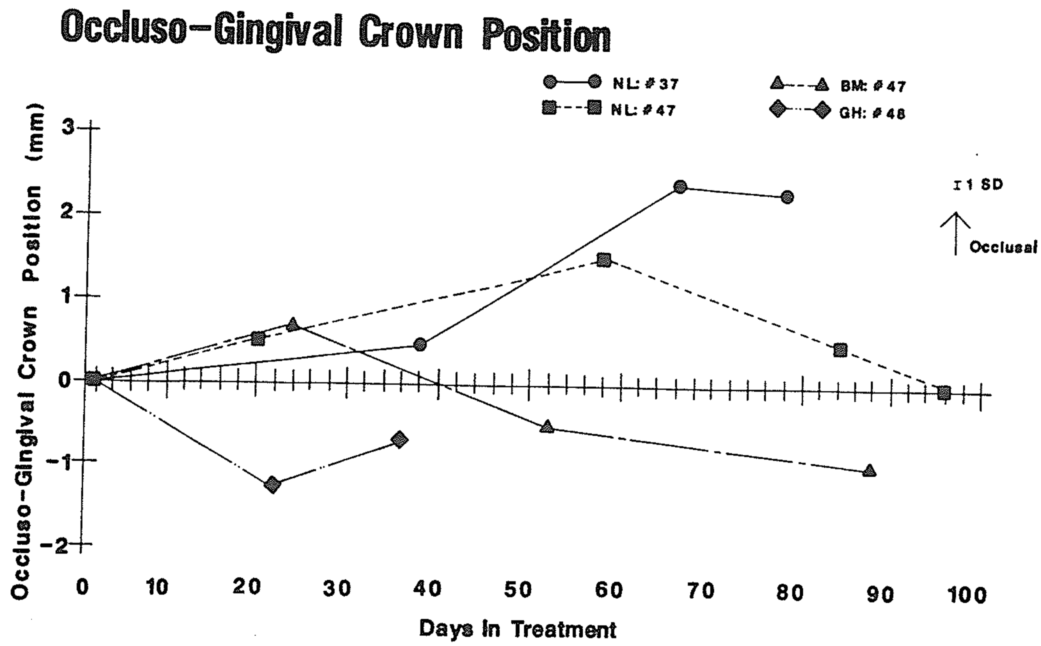


Figure 20

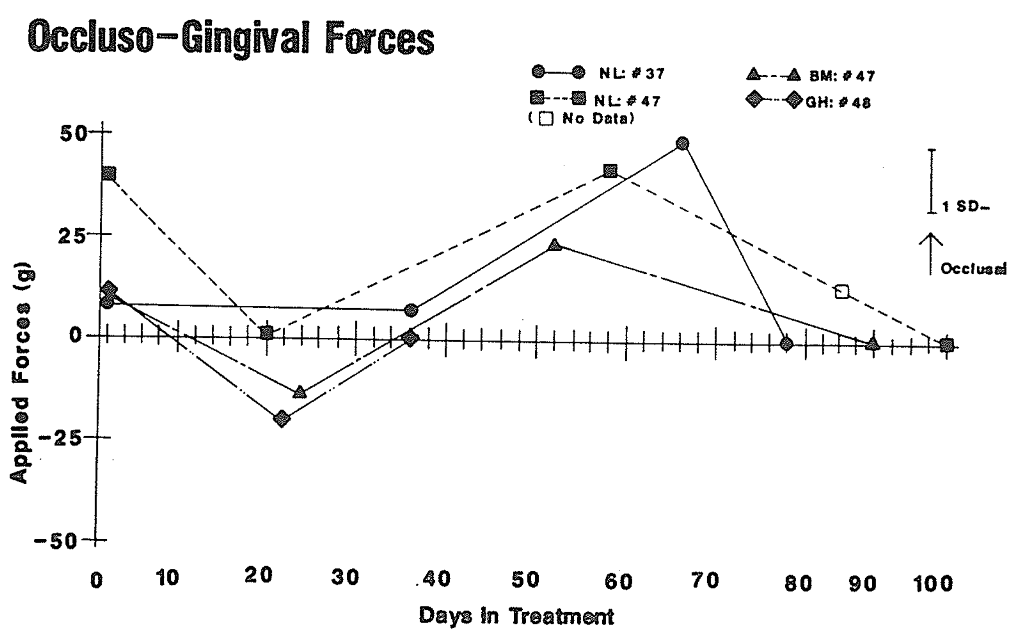


Figure 21

previously, some "false" extrusion of the crown (approximately 0.6 millimeters) was to be expected as the molar uprighted. An additional occlusal movement of the tooth of approximately 1.4 millimeters occurred.

The measured force system for patient NL(#37) varied from 35 to 0 grams of measured force and indicated that an occlually directed force was felt at the bracket. It was interesting to note that this occlusally directed force was similar in magnitude to occlusally directed forces measured at the bracket for the other molars which used the BUS. However, the molar which used the T-Loop (NL(#37)) tended to move occlusally the most. This might have been due to the geometry of the T-loop appliance which was more flexible in the occluso-gingival direction than the BUS and thus, allowed more occlusal movement of the molar.

In patient NL(#47), where a BUS was used, the average occluso-gingival crown movement of the molar first showed occlusal movement and then gingival movement so that the final occluso-gingival molar position was the same as the initial occluso-gingival molar position.

The initial occluso-gingival force measured at the bracket indicated that an occlusally directed force was present. The range of the measured magnitude of this force tended to "jiggle" within 50 to 0 grams. This "jiggling" of the occluso-gingival forces possibly reflected the errors of measurement of the machine. Also, as the crown position changed as the molar uprighted, occlusal forces could have changed to gingival forces due to the stiffness of the BUS in this dimension with the result that the molar crown began to move gingivally.

In both patients GH(#48) and BM(#47), the final average molar position seemed to be approximately one millimeter more gingival relative to their original positions (see Figure 20).

In general, the applied force systems shown in the occluso-gingival direction in Figure 21 accounted for the observed direction of crown movement. Only in one instance, at appointment three for BM(#47), did an initial occlusally directed force result in a gingival movement of the crown at the next appointment. Because the path of the molar and the changes in force systems from appointment to appointment are only approximated by the lines joining tooth position, perhaps the initial measured force system changed as the tooth position changed so that actually a net gingivally directed force was observed. The magnitudes of the measured forces for each of these molars was small and varied within 50 grams.

It was particularly evident in this range of force measurement that the 3% error of the machine, which gave a total range of 60 grams of variation for +/- 1 standard deviation was important. The range of the measured occluso-gingival force values were all less than 60 grams which could account for some of the results observed.

C. BUCCO-LINGUAL POSITION

In all cases of tooth movement measured in the bucco-lingual direction, the crown of the molar ended up in a more buccal position than when it started. This varied from one to slightly more than two millimeters (see Figure 22).

The applied force systems (see Figure 23) varied greatly in this dimension especially with the BUS which is a stiff appliance in this dimension. The T-Loop (patient NL(#37)), which is less stiff also showed smaller measured forces in this dimension. In patient NL(#37) and NL(#47), the measured bucco-lingual forces were quite small varying between 90 grams and 60 grams respectively. However, the amount of buccal tooth movement was very similar to patient BM(#47) who showed the greatest variation in applied bucco-lingual forces of approximately 200 grams.

Relative buccal crown movement, when compared to the original position of the molar, is actually desirable due

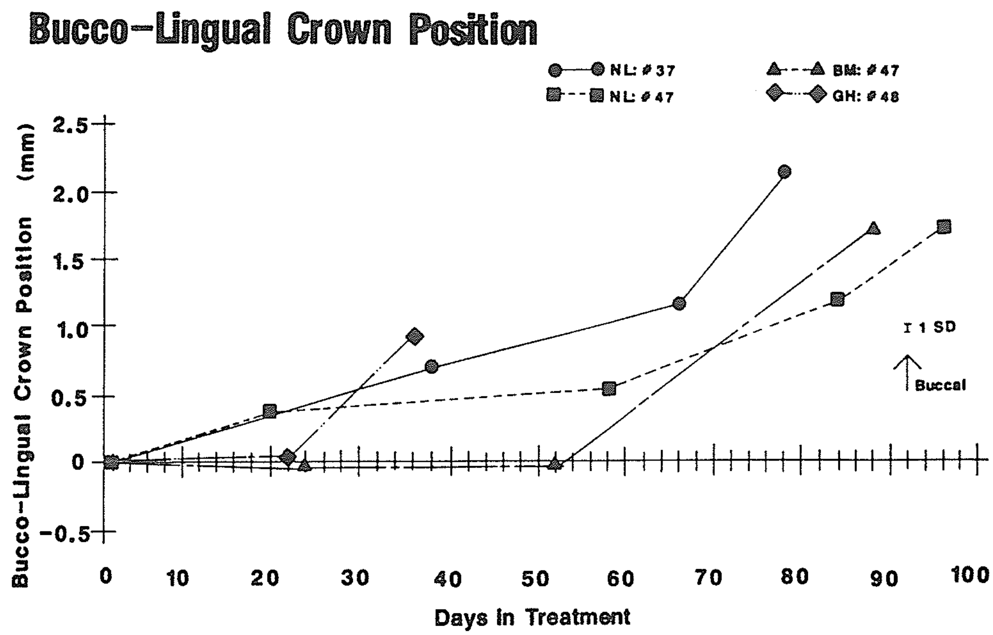


Figure 22

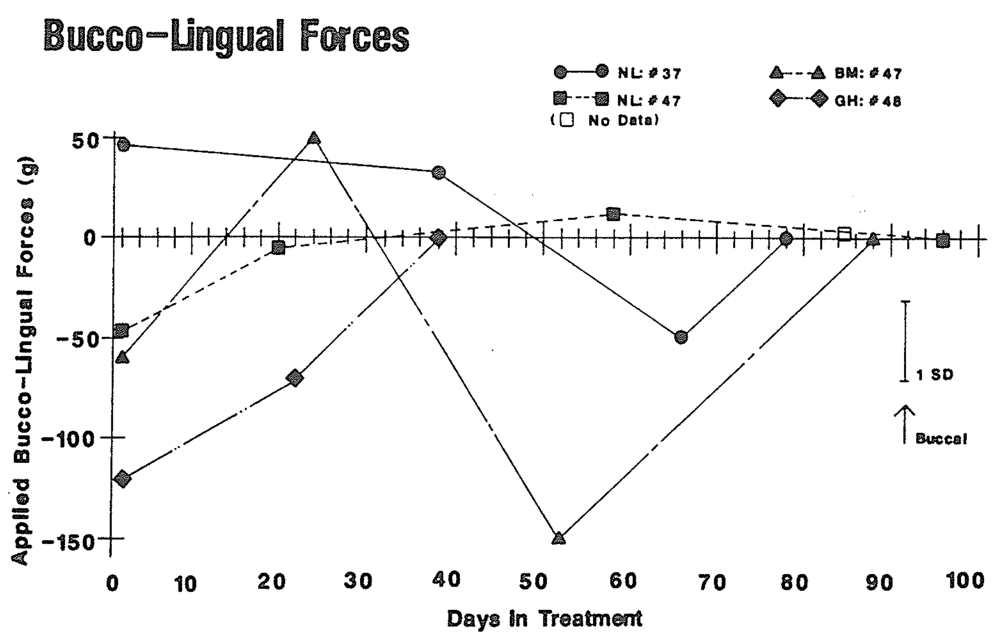


Figure 23

to the shape of the alveolar arches. As a tooth assumes a more distal position in the arch it enters a wider portion of the arch which is reflected in a relative buccal crown movement. In this investigation, distal crown movement of the molar was desirable as the molar uprighted so that, relative to the bucco-lingual axis system, buccal crown movement of the molar would also be desirable. Perhaps the initial lingually-directed forces were present for only a short period of time as the molar changed position.

4.1.6 MESIO-DISTAL AND BUCCO-LINGUAL ANGLES

The calculated amount of molar crown rotation about the mesio-distal (see Figure 24) and/or bucco-lingual (see Figure 26) axes was small (less than 10 degrees) as measured from the reference axes. However, because molar uprighting involved changes of the occlusal surface relative to the reference axes, calculated rotations in the bucco-lingual and mesio-distal directions carried errors larger than the +/-2.5 degrees calculated in section 4.1.2 and tended to exaggerate the actual rotations about these axes. Thus, the values shown in Figures 24 and 26 were measured from the changes in angles of wires attached to the acrylic splints using a protractor. These values indicated that less than 7.5

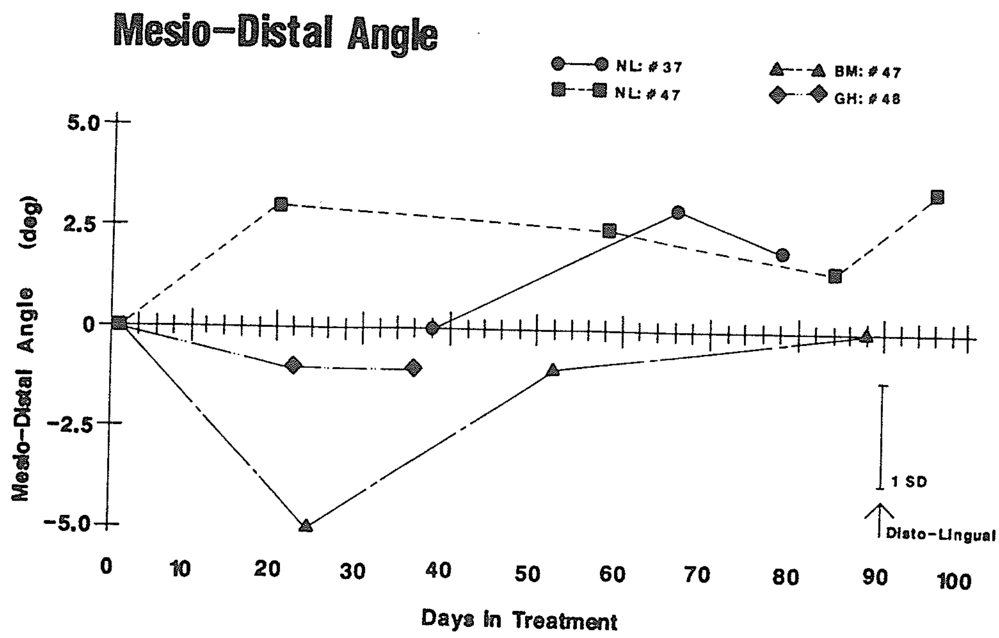


Figure 24

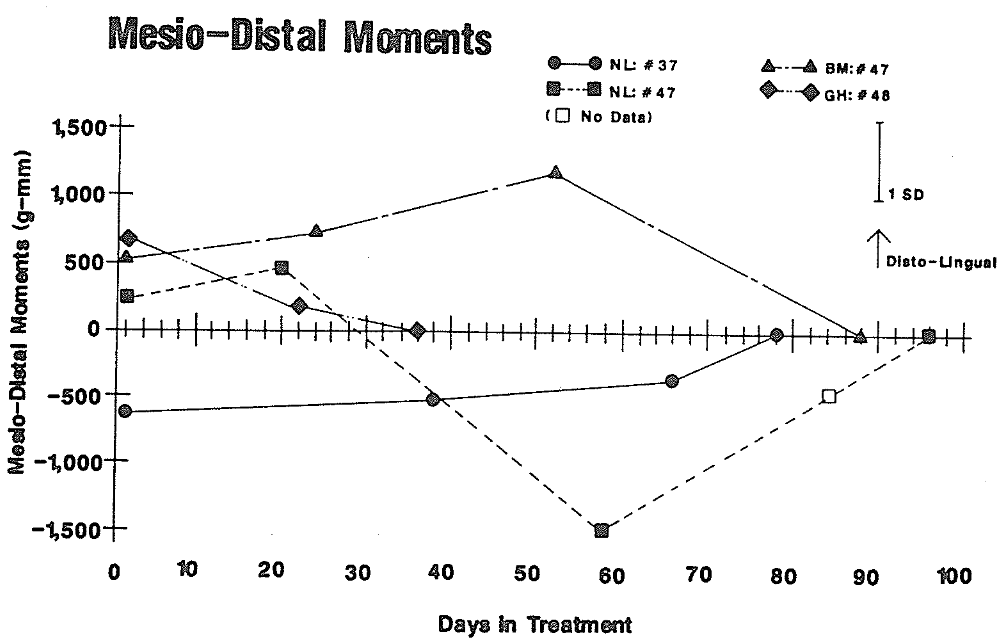


Figure 25

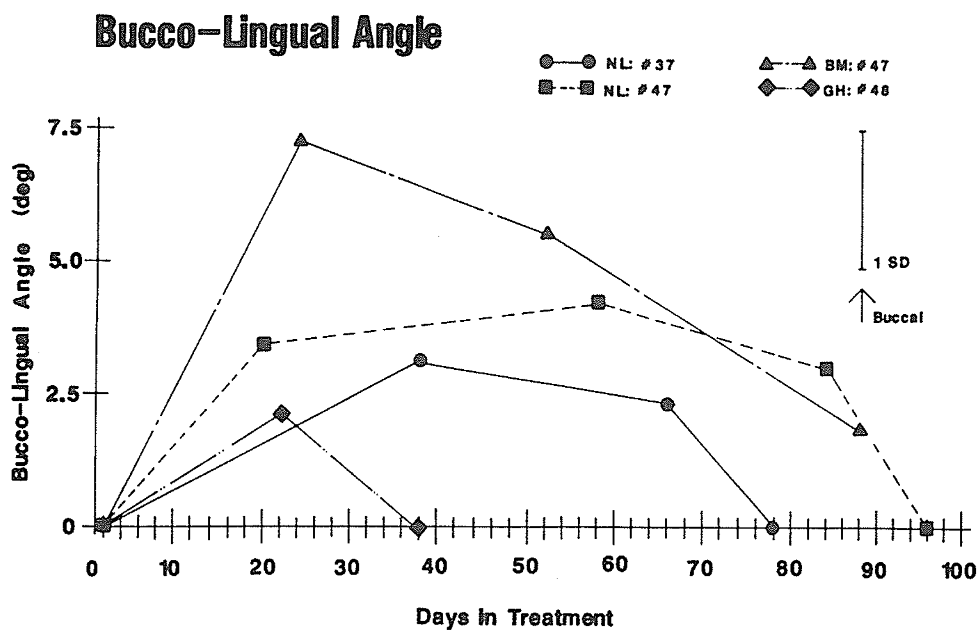


Figure 26

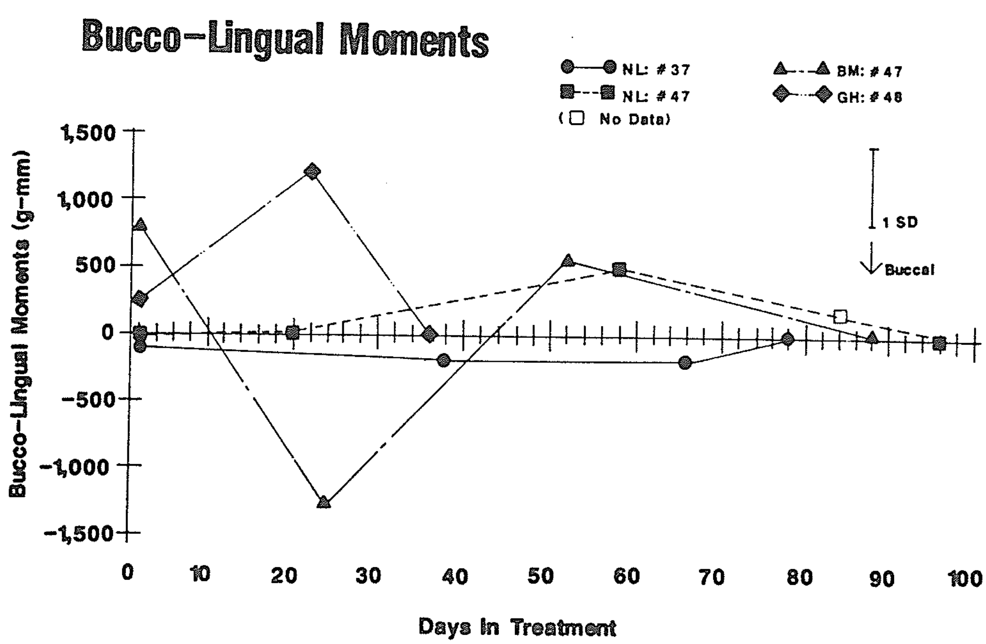


Figure 27

degrees of angular change in any one of the mesio-distal or bucco-lingual directions occurred in all situations during the course of uprighting.

The measured moments that would be expected to produce the mesio-distal (see Figure 25) and/or bucco-lingual (see Figure 27) rotations were occasionally quite large. However, these large moments were probably due to the high stiffness of the appliances in these directions. Any small change in tooth movement would then result in a large reduction of the applied moment with the result that, clinically, the tooth would not change its position significantly.

Ideally, though, spurious moments (moments in directions other than those wanted) should be minimized. Because moments were measured for rotations other than the desired uprighting moment, it might be that the appliances that were tested in this investigation are not the most desirable for uprighting mesially tipped molars.

The observed tooth movement did not always seem to correspond to the applied force systems. This discrepancy could have been due to a combination of several different factors.

Firstly, the machine measured to an accuracy of 3 percent which is an actual range of +/- 30 grams and

+/- 600 gram-millimeters. Thus, some of the observed values could be due to machine inaccuracies particularly when the observed values were close to zero and could have involved a change of sign indicating a corresponding change in direction of the force system.

Secondly, the _in vitro_ force system analysis was only a "snapshot" of the initial force system at each activation. Thus, in the time lapse between appointments, the force system could have changed as the molar uprighted. More frequent impressions and force system measurements might actually show a very closely related applied force/tooth movement response.

Other effects such as friction and ligation could have affected the measured force systems. No constraints were placed in the wire to the distal of the molars to be uprighted so that, theoretically, the wire was free to slide in the bracket if necessary as the tooth uprighted about its centre of resistance. Also, ligation pressure was not measured. Only a standard "clinical" force was used to ligate the molars. However, this could have varied from the _in vivo_ to _in vitro_ situation resulting in some variation in actual and measured force systems. Sullivan (1982) recognized the variability of ligature tension.

4.2 CONFIDENCE IN TECHNIQUE

The results of investigations into both the accuracy of measuring tooth movement and the accuracy of the technique used to determine *in vivo* applied force systems indicate that they are quite adequate for the investigation of molar uprighting.

4.2.1 TECHNIQUE FOR MEASUREMENT OF APPLIED FORCE SYSTEMS

Since intraoral force and moment measurement is virtually impossible, the duplication of the *in vivo* clinical situation *in vitro* both in terms of replicating the bracket-to-bracket relationship as well as the loop used to produce the force system is critical.

To achieve the *in vitro* bracket-to-bracket duplication, passive templates made of two pieces of wire joined by acrylic were used. Once this template was removed, its passivity was checked by placing it back into the molar and bicuspid bracket. In all cases, on clinical examination, the passive template fitted passively into the brackets. Thus, the template replicated the *in vivo* bracket position.

The other important aspect of this part of the technique was to ensure that the force system applied by the *in vitro* loop was similar to that force system applied intraorally. Appendix A reports the results of this investigation. The BUS and the T-loop could be duplicated to within +/- 20% in the primary force activation (mesio-distal) and the primary moment activation (that of uprighting). This +/- 20% range of accuracy of duplication also includes the machine error, which was quite large, when using it at the low end of the scale. However, this accuracy was certainly an improvement over the great variation in force systems reported in the literature (see Table I in chapter 2) often for similar appliances. Thus, the force and moment data generated by the machine from these duplicate loops was considered adequate for this project in which other techniques were developed and tested.

The accuracy of the machine had been verified by previous research. However, in order to ensure accuracy, the machine was calibrated prior to final data collection.

The main limitation in using this machine to measure forces and moments was due to the 3% total error of full scale. This error amounted to +/- 30 grams for the measured forces and +/- 600 gram-millimeters for the measured moments. Some of the actual measured forces and moments for the four molars often fell within this range. Therefore, this could account for some of the variation seen in the measured force systems. However, it will be emphasized here that, even though the range of the machine was not ideal for this investigation, the local relative errors were much smaller than the total error range would suggest. This meant that trends were noted and were considered accurate when compared to one another. Also, this machine was available for the initial tests to show that other aspects of the technique were viable. The construction of another machine for force measurements could then be considered with other factors as improvements to the technique.

4.2.2 TOOTH MOVEMENT MEASUREMENT TECHNIQUE

Appendix B reports the accuracy with which measurements can be made using the apparatus developed for this investigation. With the author making the measurements, tooth movement in three dimensions can be measured with standard deviation of 0.08 millimeters in the mesio-distal direction, 0.08 millimeters in the occluso-gingival direction and 0.10 millimeters in the bucco-lingual direction. These values were certainly acceptable and compared favorably with those quoted in the literature. When these values were used in calculating the error for rotational movements, a standard deviation of

+/- 2.5 degrees could be expected.

A stable reference system was very important when attempting to gain information regarding tooth movement. In this investigation, the anchorage segment was the reference system to which molar movement was related. Thus, it was important that minimal movement of the anchorage unit occur.

The anchorage unit was prepared with heavy dimension arch wires, reinforced with a lingual arch and an acrylic splint and allowed to "settle" prior to beginning the molar uprighting. In this manner, minimal movement of the anchorage segment was expected.

The stability of the anchorage segment was checked in three different ways: fit of the acrylic splint on each cast, comparing distances between the same points on the anchorage segment to the respective reference axes and superimposing occlusograms taken from subsequent casts onto the marked points in the anchorage unit (see Appendix C). Each of these methods showed that movement within the anchorage unit as well as movement of the whole anchorage unit was insignificant. Thus, reliable reference axes could be established from which to measure the changes in molar position as uprighting occurred.

One of the limitations of this measurement system was the amount of time taken to measure a single cast. Approximately one to one and one-half hours was needed to measure a single cast. For an investigation such as this where only a limited number of molars was used, this was not a problem. However, if a much greater number of casts had to be studied, time constraints and tedium would become a limiting factor.

4.3 CAPABILITIES OF THE TECHNIQUE

The orthodontic literature makes frequent reference to centres of resistance and the effects of force systems applied at some distance from the centres of resistance of teeth. To date, there is no simple technique to determine centres of resistance of teeth nor was this an objective of this investigation. However, this technique has the ability to relate force systems applied to any possible existing centre of resistance (if and when they can finally be accurately measured clinically) by virtue of the development of computer programs which enable these calculations to be made. Thus, it was interesting to estimate a centre of resistance and look at both tooth movement and the applied force systems obtained. One molar, that of BM(#47), will be discussed in this section.

4.3.1 TOOTH MOVEMENT

Figure 28 shows a two-dimensional plot of tooth movement as observed from the buccal (along the bucco-lingual) axis of the tooth. The coordinates of the molar at each appointment in the occluso-gingival and mesio-distal direction were combined with the respective degrees of uprighting at each appointment. Thus, a line, representing the long axis of the molar, was used to represent the entire tooth as it uprighted. In this way, a clearer picture of the path of the molar as it uprighted is provided.

Similarly, two-dimensional plots for the other dimensions of molar movement can be drawn. Because the rotational movements in the other dimensions were so small, these plots will not be shown.

4.3.2 FORCE SYSTEMS AT THE CENTRE OF RESISTANCE

Computer programs for the I.B.M. computer allowed quick calculation of eqivalent force system for any chosen point on the tooth. In this manner, any tooth size or shape could have its force system analyzed at its centre of resistance provided this could be accurately determined.

Patient BM : Molar Position

Scale - 5:1

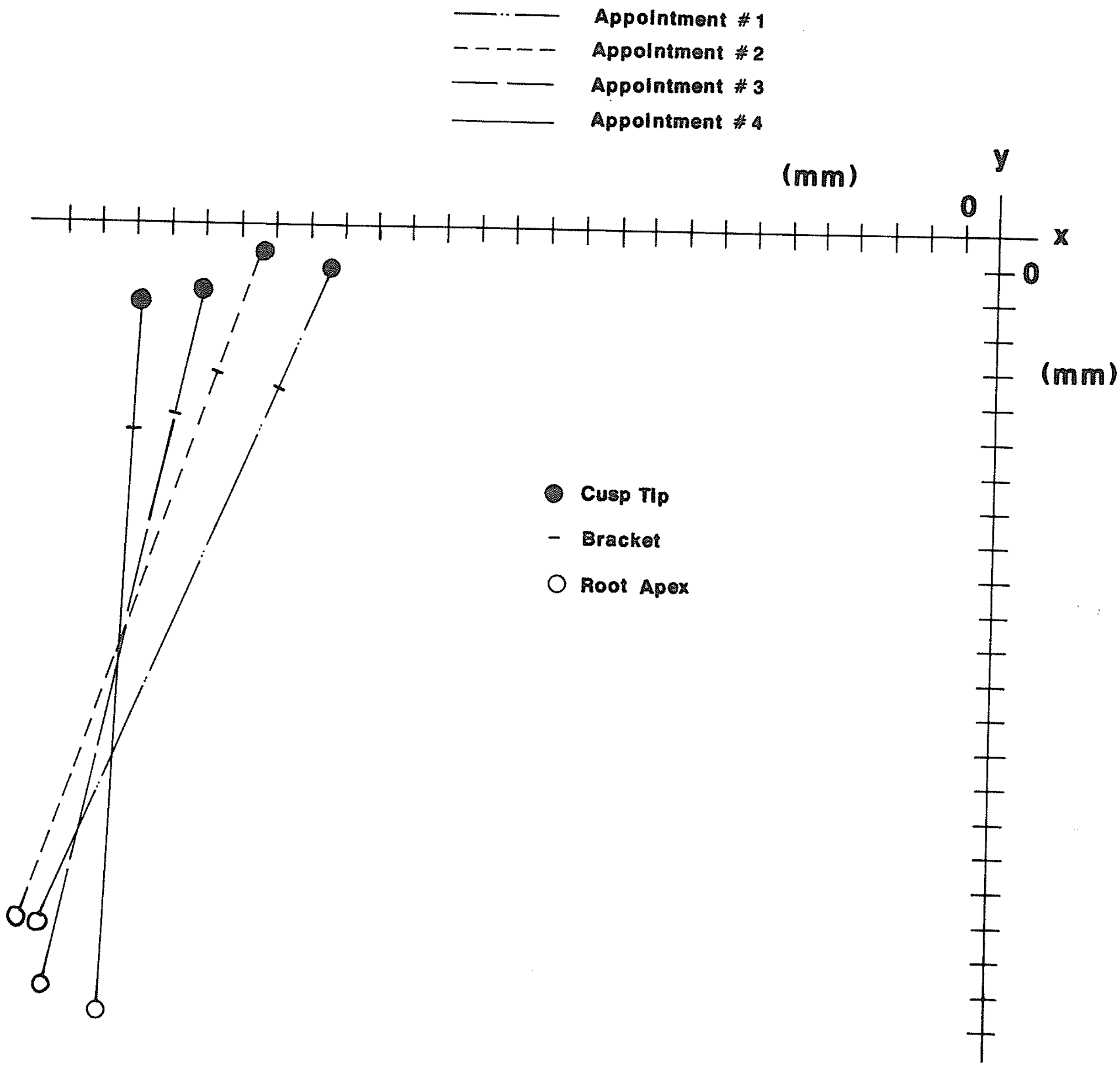


Figure 28

To further illustrate this technique, an estimated centre of resistance of 10 millimeters from the molar bracket was chosen for patient BM(#47). Using the principles of mechanics, forces, applied at any point, are transferable. Thus, the forces measured at the bracket and graphed in Figures 18, 20 and 22 would remain the same when the equivalent force system is placed at this estimated centre of resistance. However, the moments must change to account for the change in relocation of the forces.

Figure 29 shows the magnitudes of the uprighting moments felt at the centre of resistance for patient BM(#47) at each appointment. These were compared to the values obtained at the bracket as previously shown in Figure 16 and repeated here to facilitate comparison. In all cases, the measured uprighting moments at this estimated centre of resistance of the molar were smaller than the uprighting moments measured at the bracket. This was due to the fact that a mesially directed force at a distance of 10 millimeters from the centre of resistance produced a moment opposite to that placed in the appliance. This moment, producing a mesial crown tipping tendency, slightly reduced the amount of uprighting moment available and was reflected in the values on the graph

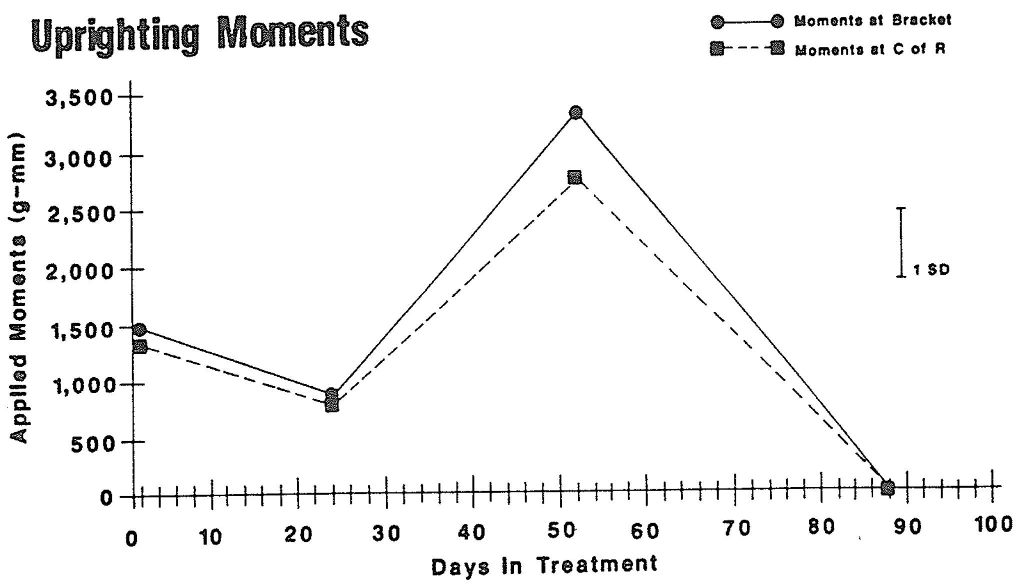

Uprighting Moments
Moments at Bracket
Moments at C of R
Applied Moments (g-mm)
3,500
3,000
2,500
2,000
1,500
1,000
500
0
1 SD
0
10
20
30
40
50
60
70
80
90
100
Days In Treatment

Figure 29

(see Figure 29).

To check that the measured force in the mesio-distal direction actually changed the uprighting moment values when measured at the centre of resistance as shown in Figure 29 was easily done. Multiplication of each of the measured mesio-distal values shown in Figure 18 by a factor of 10 (the distance from the bracket to the estimated centre of resistance) did in fact give the measured moment values at the bracket to an accuracy of 70 gram-millimeters. This small error could partially be due to the fact that the centre of resistance as related to an axis system placed at the bracket changed as the molar uprighted. In other words, the distance between the centre of resistance and the bracket changed during molar uprighting and was not taken into account in these examples showing the capabilities of the technique. This would not occur in translation where the centre of resistance would remain in the same relation to bracket.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The conclusions from this investigation are as follows:

(1) The primary objective of molar uprighting with distal crown movement was achieved in all cases. No unexpected clinically significant movements occurred.

(2) The paths of the molars uprighting when the Burstone Uprighting Spring was used appeared to be similar. The T-Loop produced a more erratic pattern of molar uprighting before its final position was achieved compared to molar uprighting using the Burstone Uprighting Spring.

The main undesirable movement in molar uprighting of extrusion of the crown did not appear to be large. In fact, in the cases using the Burstone Uprighting Spring, no net extrusion of the crown was found. In the case in which the T-Loop was used, approximately two millimeters of crown extrusion was found. A sample of one did not allow firm conclusions to be drawn but variations in the flexibility of these loops in this direction may have been a factor in the observed results.

(3) The molars seemed to upright relatively constantly, at approximately 6 degrees per month, and the rate of uprighting was not related to the magnitudes of the applied uprighting moments measured in this investigation.

(4) In this investigation, the older patients (GH(#48) and BM(#47)) averaged twice the applied uprighting moment than the younger patient (NL(#37 and #47)). However, the rate of molar uprighting was similar in all cases. This may have been due to effects of the variables of age and/or sex and/or the fact that the lowest measured moment of this investigation exceeded the optimum moments for molar uprighting and thus, no differences in molar urpighting occurred above this value (Quinn and Yoshikawa, 1985).

(5) Anchorage segment movement was insignificant in this investigation, indicating that, if the anchorage was prepared carefully, a stable segment could be used to calculate reference axes so that desired tooth movements could be determined and unwanted tooth movements could be minimized.

(6) The technique used in this investigation provided an adequate method of measuring tooth movement, namely molar uprighting, in response to known applied force

systems also measured in three dimensions simultaneously. The accuracy of this technque was also supported by results from a similar investigation into three-dimensional assessment of cuspid retraction (to study translation: Duff, 1987).

(7) The capabilities of the machine used in this investigation to measure force systems included being able to vary the centres of resistance of teeth so that teeth of different dimensions could be analyzed. Thus, more complete knowledge of tooth movement could be obtained in relation to known force systems particularly in cases, such as molar uprighting, where clinical criteria would dictate if movement of the centre of resistance was required during uprighting.

5.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the results of the present study, recommendations for improvements to the measuring technique include:

(1) The equipment used to measure the applied force systems three dimensions simultaneously could be improved. The range of the machine used to measure the applied force systems was known to be inappropriate for this investigation as the

magnitudes of the force systems applied in the clinical situations were relatively small compared to the maximum range of the machine. Thus, a new machine with the appropriate measurement range could be made.

(2) The apparatus used to measure tooth movement was accurate but rather slow. Use of a measuring apparatus (i.e. Reflex Micrometrograph) which would allow points to be digitized, allow easier duplication of subsequent cast positions to the calculated reference axes and allow distances to be calculated from the digitized points would be of great benefit to this aspect of the technique.

Some of the research into tooth movement that would help quantify the effectiveness of orthodontic mechanotherapy are:

(a) Shorter time intervals could be used to more completely record tooth movement and force and moment changes. Different appliances for molar uprighting could be studied using different wire types, diameters etc.

(b) Greater variations in the applied uprighting moments could be investigated in order to determine the influence of magnitude of applied force systems on rate of tooth movement and pain response.

(c) Expanding the data base by increasing the number of patients so that more information regarding tooth movement in response to known applied force systems could be made. The influence of variables such as age, race, periodontal health etc. might then be determined.

Investigations such as this, on tooth movement response to known applied force systems measured in three dimensions, might be combined with biological investigations of the response of the periodontal ligament to various force systems.

CHAPTER VI

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APPENDIX A

LOOP DUPLICATION STUDY

APPENDIX A

LOOP DUPLICATION STUDY

As indicated in chapter 3.2.5, two identical uprighting loops, one for producing tooth movement, the other for an *in vitro* determination of the force systems applied, were required for each phase or treatment. Clearly this method of assessing the *in vivo* force system depended on producing two virtually identical appliances. It was, therefore, necessary to determine that the accuracy of replication of appliances made by the author was adequate for this purpose.

A.1 MATERIALS AND METHODS

The two types of loops that were used in the clinical experiment to upright molars were tested, the Burstone Uprighting Spring (BUS) and the T-loop.

Ten of each of these loops were bent to a template in order to make each loop as similar in form as possible. Again, the same wire as used in the actual clinical settings was used in this investigation, 0.457 millimeter (0.018 inch) square stainless steel wire (Ormco).

Each loop was then mounted in the measuring machine so that the forces and moments measured at identical activations could be compared. The gantry used for holding and activating the loops and for the individual activations in this investigation was a modification of a system previously used by Levine (1985).

The loops were placed in the centre of the two *in vitro* teeth (ie. the molar to be uprighted and the bicuspid "tooth"). The ends of the loops were held rigidly in this activation assembly. This eliminated any variations in measured force systems due to friction, ligation, etc. and therefore, any variation in measured force systems would be due to variations in the loop.

Only the primary forces, mesio-distally directed forces and moments, the uprighting moment about the bucco-lingual (or "z" axis) will be reported here as these are the most important for molar uprighting. The activations in all directions were controlled from the Hewlett-Packard computer. The computer program allowed the desired activations to be entered. Continuous monitoring during the actual activations via the Hewlett-Packard computer ensured that the desired activation was achieved.

From the data acquired, forces and moments delivered by each appliance for the respective activations were calculated and stored in digital form on magnetic tape. This data was then transferred into the I.B.M. computer where it was stored on floppy discs. Table A-I shows the activations used for these loops. The activation sequences for the T-loop and the Burstone uprighting spring had to be different due to the difference in stiffness of these two loops.

TABLE A-I

	ACTIVATION NUMBER	mesio-distal activations (mm)	molar uprighting activations (degrees)	bucco-lingual activations (mm)
BUS	1	0.0	0.0	0.0
	2	0.0	15.0	0.0
	3	0.0	30.0	0.0
	4	-1.5	0.0	0.0
	5	-1.5	15.0	0.0
T-Loop	1	0.0	0.0	0.0
	2	0.0	15.0	0.0
	3	0.0	30.0	0.0
	4	-1.5	0.0	0.0
	5	-1.5	15.0	0.0
	6	-1.5	30.0	0.0
	7	-1.5	0.0	0.0
	8	-3.0	0.0	0.0
	9	-3.0	15.0	0.0
	10	-3.0	30.0	0.0

A.2 RESULTS AND DISCUSSION

The data for the respective activations using the BUS and the T-loop are graphed in figures A-1, A-2, A-3 and A-4.

The variation in measured forces and moments for each of these primary activations of mesio-distal force and uprighting moments generally were within a +/- 20% range. This meant that the loops could be duplicated to within a +/- 20% accuracy. There were less variations measured in the ten T-loops than in the BUS loops. This variation could be due to differences in stiffness of the appliances. A stiffer appliance would produce more errors in applied force systems because the variation between degrees of activation is greater.

There was more variation in the secondary forces and moments measured when each loop was compared in this investigation.

A.3 CONCLUSIONS

This investigation showed that the forces and moments delivered by loops bent to templates were sufficiently similar especially when compared to the great variation evident in the orthodontic literature (from 64 to 1515 grams). Therefore, loops bent to a template could be used interchangeably for situations requiring both linear and rotational activations. Thus, when a Burstone uprighting

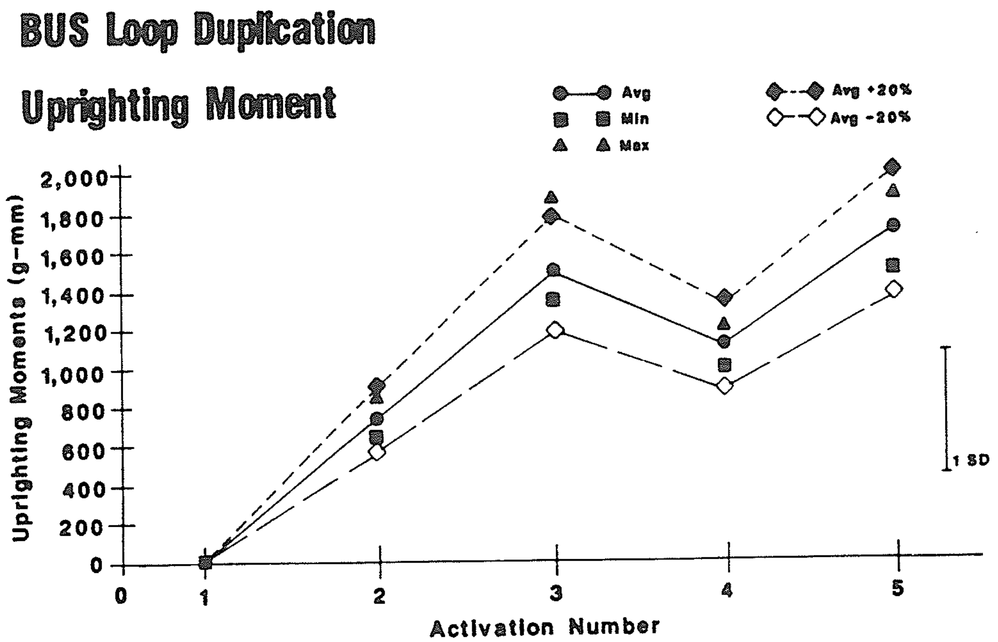

Figure A-1

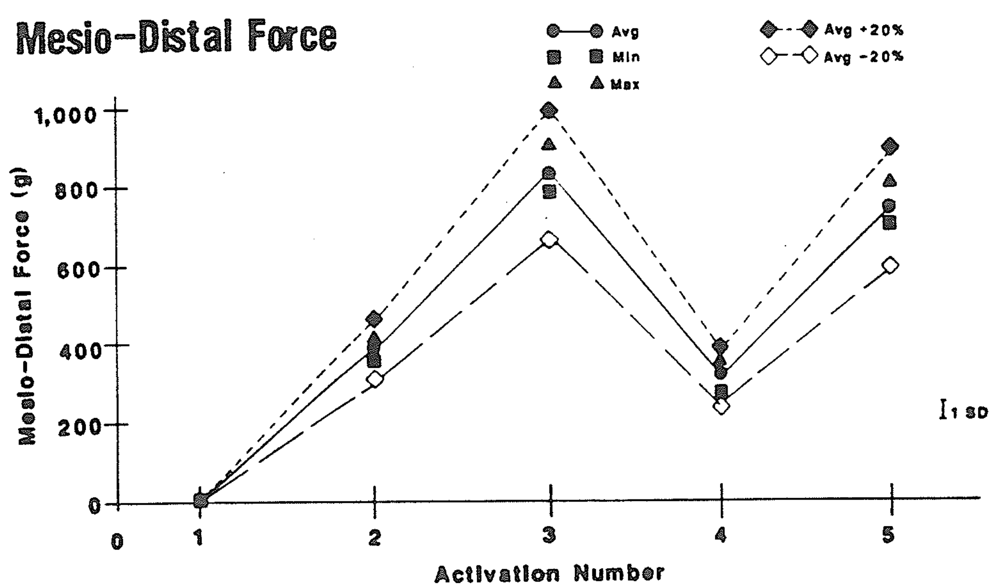

Figure A-2

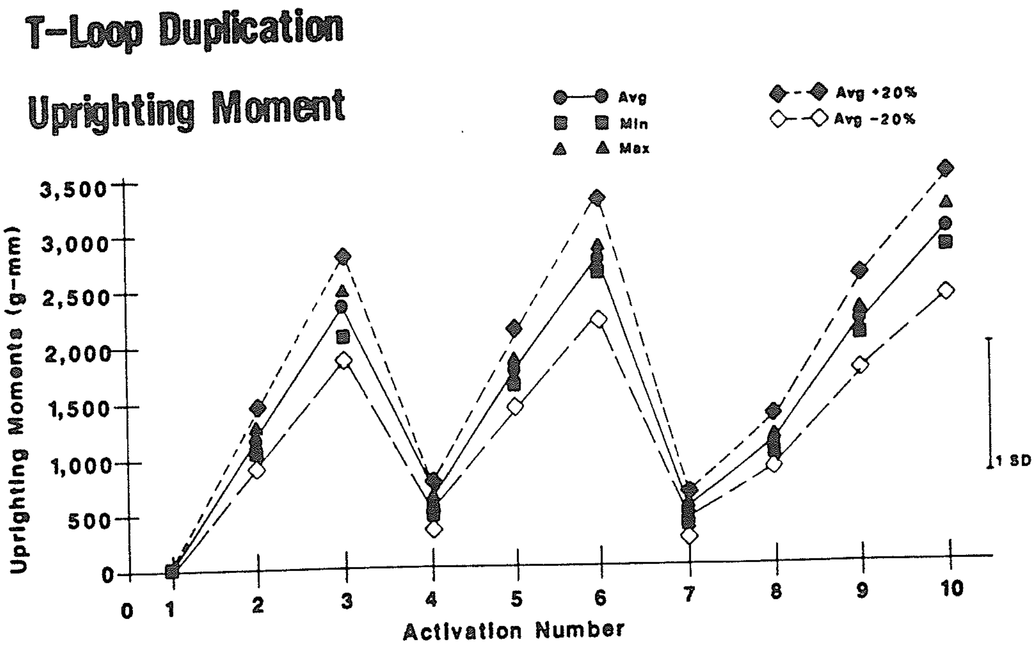

Figure A-3

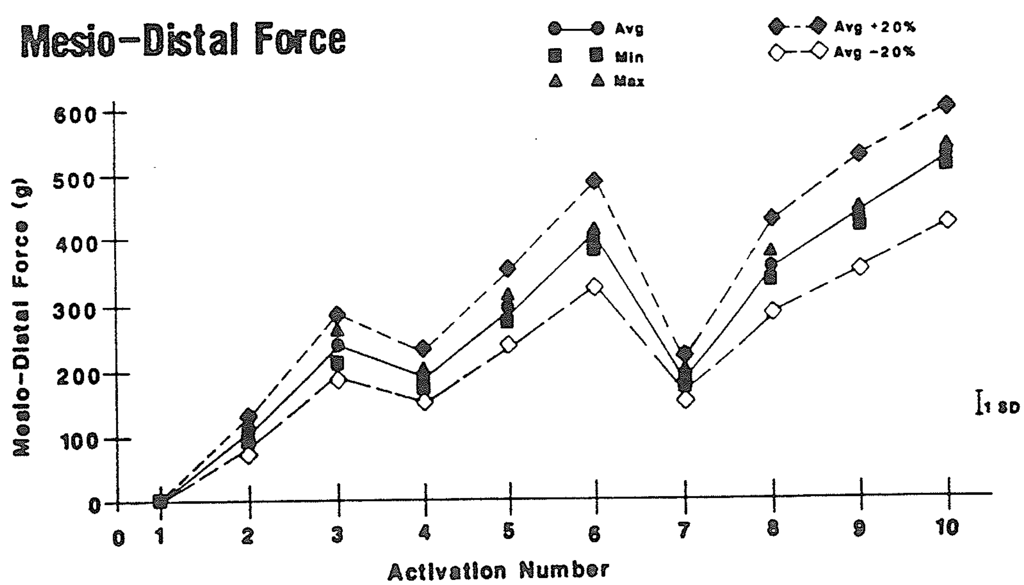

Figure A-4

spring or T-loop was placed into a patient to deliver the necessary force system, a duplicate loop bent to a template and activated in a similar manner could be expected to provide a similar force system. This duplicated loop could then be taken to the laboratory to have its force system analyzed. The force and moment values obtained from activation of this *in vitro* appliance, which was the same as the activation of the *in vivo* appliance, could then be used to describe the force system delivered by the *in vivo* appliance. In this manner, the force system for a particular loop could be determined to an accuracy not significantly different from that expected for other measurements in the tooth movement study.

APPENDIX B

CAST MEASUREMENT STUDY

APPENDIX B

CAST MEASUREMENT STUDY

A study was undertaken to deterimine the errors likely to be introduced by using study casts as a medium for measuring *in vivo* tooth position. This study was concerned with the ability to accurately identify and measure the same point on successive casts in order to be able to quantify tooth position changes.

B.1 MATERIALS AND METHODS

The investigation was divided into two parts, one to identify the intraoperator variability and the other to identify the variability of using alginate impression material and orthodontic plaster as a means of determining tooth position changes.

B.1.1 INTRAOPERATOR VARIABILITY

This investigation consisted of repeatably locating a single point on a maxillary study cast (poured in orthodontic plaster) made from an alginate impression of a plastic master cast. The buccal cusp of the upper left first bicuspid (#24) was located in the three dimensions using the measurement apparatus described in section

3.3.2. The variation in values obtained indicate the variation of repeatably and precisely locating this point on the cast.

B.1.2 TECHNIQUE ERROR

Using alginate impressions and study casts from which to measure tooth position changes introduces errors other than operator errors. This investigation was undertaken to determine the error in taking measurements using study casts.

Impressions for four study casts, using Fast Set Alginate, were made from the plastic master cast referred to above. These impressions were then poured in orthodontic plaster. A template was made to fit over the occlusal surfaces of these study casts in order to be able to locate the same landmark on subsequent casts. In this manner, five landmarks were identified. These were the mesio-buccal cusp tip of the upper right second molar (#17), the buccal cusp of the upper right second bicuspid (#15), the cusp tip of the upper right cuspid (#13), the buccal cusp of the upper left second bicuspid (#25) and the mesio-buccal cusp of the upper left second bicuspid (#27).

A reference axis was established for each of the three mutually perpendicular axes as described in section 3.4.2 using the measurement apparatus described in section 3.3.2. Thus, five distances from the above listed five points were made to the reference axes in the three dimensions.

Measurements from the four study casts were compared with one another as well as being compared with measurements made using these same points on the master plastic cast.

B.2 RESULTS AND DISCUSSION

The results for each of these investigations are shown below.

B.2.1 INTRAOPERATOR VARIABILITY

Table B-1 shows the data and results obtained in this investigation. It was found that the error associated with locating the same point in all three dimensions was very small. The errors were within +/- 0.04-0.05 millimeters and depended on the dimension being measured. Thus, not all dimensions produced the same amount of accuracy. This is in accordance with results in the literature as reported in section 2.1.

TABLE B-1

INTRAOPERATOR VARIABILITY

Trial #	MESIO-DISTAL (mm)	OCCLUSO-GINGIVAL (mm)	BUCCO-LINGUAL (mm)
1	56.70	57.06	37.74
2	56.60	57.06	37.68
3	56.68	57.14	37.64
4	56.68	57.08	37.74
5	56.72	57.12	37.74
6	56.62	57.10	37.72
7	56.64	57.16	37.62
8	56.68	57.16	37.70
9	56.70	57.12	37.66
10	56.64	57.04	37.64
11	56.64	57.08	37.60
12	56.68	57.06	37.66
13	56.66	57.06	37.64
14	56.60	57.08	37.70
15	56.64	57.12	37.60
16	56.66	57.14	37.76
17	56.72	57.06	37.70
18	56.60	57.14	37.60
19	56.64	57.14	37.66
20	56.62	57.00	37.60
21	56.62	57.10	37.70
22	56.64	57.14	37.66
23	56.68	57.11	37.64
24	56.68	57.14	37.72
25	56.62	57.12	37.64
26	56.66	57.06	37.64
27	56.70	57.12	37.70
28	56.60	57.14	37.72
29	56.70	57.12	37.70
30	56.64	57.10	37.72
STANDARD DEVIATION	0.04	0.04	0.05

B.2.2 TECHNIQUE ERROR

It was found that the standard deviation of the measured distances between selected points on each of the four study casts was equal to or less than 0.10 and shown in Table B-2. Again, it was found that there was variation in the accuracy of measurement depending on the axes in which the measurements were taken.

When the measured distances from the study casts were compared to the same measurements made on the plastic master cast greater variations in these measured distances were found. The largest variation in measured distances between the master cast and the four study casts was 0.38 millimeters. The average variation in measured distances between the master cast and four study casts was 0.24 millimeters and though quite small, was larger than the variations between measured distances for the four study casts only.

The slightly greater variation between the master cast and the study casts was to be expected as alginate material and orthodontic plaster are not the best reproductive materials. However, the variation between distances on each of the study casts was sufficiently small, as shown in Table B-2, that comparisons from study cast to study cast could be made with good confidence.

TABLE B-2
MEASUREMENT OF TECHNIQUE ERROR

DISTANCES BETWEEN MARKED POINTS AND REFERENCE AXIS IN THE MESIO-DISTAL DIMENSION (mm):

	Point Identified				
	17MB	15B	13B	25B	27MB
Cast #1:	14.06	3.48	16.42	4.68	10.54
Cast #2:	14.06	3.42	16.38	4.78	10.54
Cast #3:	14.21	3.44	16.49	4.63	10.69
Cast #4:	14.12	3.38	16.64	4.70	10.60
SD:	0.06	0.10	0.10	0.05	0.06

AVERAGE SD FOR DISTANCES IN THE MESIO-DISTAL AXIS = 0.07.

DISTANCES BETWEEN MARKED POINTS AND REFERENCE AXIS IN THE OCCLUSO-GINGIVAL DIMENSION (mm):

	Point Identified				
	17MB	15B	13B	25B	27MB
Cast #1:	1.50	0.36	1.16	0.36	0.40
Cast #2:	1.43	0.33	1.13	0.33	0.37
Cast #3:	1.49	0.35	1.15	0.35	0.37
Cast #4:	1.43	0.35	1.15	0.35	0.41
SD:	0.03	0.01	0.01	0.01	0.02

AVERAGE SD FOR DISTANCES IN THE OCCLUSO-GINGIVAL AXIS = 0.02.

DISTANCES BETWEEN MARKED POINTS AND REFERENCE AXIS IN THE BUCCO-LINGUAL DIMENSION (mm):

	Point Identified				
	17MB	15B	13B	25B	27MB
Cast #1:	24.42	20.70	14.80	27.14	32.80
Cast #2:	24.39	20.77	14.77	27.15	32.79
Cast #3:	24.44	20.78	14.88	27.26	32.82
Cast #4:	24.42	20.94	14.68	27.18	32.86
SD:	0.02	0.09	0.07	0.05	0.03

AVERAGE SD FOR DISTANCES IN THE BUCCO-LINGUAL AXIS = 0.05.

The lack of variation between study casts was more important than the actual stability of the materials used as the measurements made to record changing tooth positions in the molar uprighting study were made from study cast to study cast and not intra-orally to study cast.

B.3 CONCLUSIONS

The combined variation of both intraoperator variability and errors inherent in longitudinal measurements of changes in tooth position on study casts was 0.11 millimeters for one standard deviation in all three dimensions. This meant that the points could be identified to +/- 0.11 millimeters with a probability of 68% or to +/- 0.22 millimeters with a probability of 96%.

These values compared very well with the techniques described in section 2.1 for measuring tooth positions. Thus, it was felt that, once a landmark was transferred to the casts using the above mentioned template method, the accuracy of locating this landmark was very good. In this way, information obtained from successive casts using the same landmark, could be used to relate tooth movement to applied forces and moments.

APPENDIX C

DATA FOR ANCHORAGE STABILITY

APPENDIX C

DATA FOR ANCHORAGE STABILITY

This appendix shows the actual values for comparisons of the distances between each marked point in the anchorage segment to their respective reference axes in each of the three dimensions for each measured cast (see Tables C-1, C-2 and C-3). If the anchorage segment was to be considered relatively stable, only small variations in these measured distances from cast to cast could be accepted.

It may be seen that the values listed in Tables C-1, C-2 and C-3 do not vary greatly and fall within two standard deviations as calculated from appendix B. A range of +/- 0.22 millimeters could be expected. This indicated that the teeth in the anchorage segment were stable relative to one another.

Occlusograms taken of subsequent casts and superimposed on one another for best fit of the marked points on the anchor segment and any soft tissue landmarks that could be identified, indicated that the stability of the entire anchorage segment was good as well. The anchorage units did not appear to move in any direction significantly enough to be detected by this technique.

This provided another check on the stability of the anchorage segment.

TABLE C-1
ANCHORAGE DATA FOR PATIENT NL

TOOTH #	MESIO-DISTAL DAY 1	MESIO-DISTAL DAY 19	MESIO-DISTAL DAY 54	MESIO-DISTAL DAY 84	MESIO-DISTAL DAY 96	OCCLUSO-GINGIVAL DAY 1	OCCLUSO-GINGIVAL DAY 19	OCCLUSO-GINGIVAL DAY 54	OCCLUSO-GINGIVAL DAY 84	OCCLUSO-GINGIVAL DAY 96	BUCCO-LINGUAL DAY 1	BUCCO-LINGUAL DAY 19	BUCCO-LINGUAL DAY 54	BUCCO-LINGUAL DAY 84	BUCCO-LINGUAL DAY 96
31M	12.48	12.54	12.50	12.56	12.56	2.65	2.64	2.63	2.64	2.64	0.17	0.11	0.14	0.21	0.20
31D	12.34	12.38	12.44	12.42	12.40	2.65	2.64	2.67	2.62	2.66	2.21	2.17	2.18	2.31	2.22
33	7.88	7.90	7.90	7.82	7.86	2.21	2.14	2.23	2.14	2.14	12.05	12.11	12.08	12.11	12.12
34B	2.18	2.20	2.21	2.12	2.16	1.03	0.98	0.99	1.00	0.90	18.53	18.57	18.54	18.61	18.58
34L	0.22	0.28	0.27	0.30	0.22	1.87	1.76	1.77	1.86	1.76	16.69	16.59	16.90	16.81	16.68
34M	3.42	3.42	3.51	3.42	3.40	0.47	0.52	0.59	0.48	0.58	16.11	16.07	16.04	16.09	16.08
34D	0.12	0.14	0.03	0.22	0.22	0.77	0.72	0.83	0.76	0.72	19.57	19.57	19.58	19.63	19.62
35B	4.26	4.20	4.23	4.18	4.18	0.37	0.36	0.35	0.36	0.36	22.37	22.43	22.40	22.33	22.34
35L	5.84	5.96	5.99	5.90	5.84	1.31	1.24	1.23	0.96	1.24	18.85	18.85	18.78	18.73	18.82
35M	2.78	2.74	2.75	2.86	2.80	0.89	0.94	0.99	0.96	0.86	20.13	20.09	20.14	20.19	20.18
35D	6.62	6.64	6.63	6.66	6.56	1.45	1.56	1.53	1.56	1.46	22.01	22.03	22.08	21.99	22.04
43	7.10	7.10	7.12	7.12	7.08	2.15	2.20	2.17	2.24	2.24	13.51	13.51	13.58	13.65	13.54
44B	0.28	0.10	0.17	0.14	0.18	1.23	1.28	1.37	1.24	1.42	19.51	19.45	19.48	19.43	19.44
44L	0.84	0.90	0.83	0.82	0.88	1.23	1.18	1.15	1.26	1.24	16.43	16.59	16.48	16.47	16.52
44M	2.78	2.86	2.73	2.82	2.74	0.57	0.58	0.67	0.70	0.70	16.77	16.77	16.80	16.83	16.76
44D	1.62	1.60	1.53	1.56	1.58	0.95	0.98	0.87	0.98	0.84	18.87	18.95	18.94	18.71	18.90
45B	6.08	6.02	6.05	6.00	6.00	0.37	0.36	0.35	0.36	0.36	22.39	22.33	22.36	22.43	22.42
45L	7.52	7.46	7.49	7.46	7.54	0.79	0.86	0.77	0.76	0.84	18.73	18.67	18.64	18.75	18.66
45M	4.22	4.20	4.27	4.18	4.24	0.63	0.64	0.67	0.66	0.74	20.41	20.33	20.48	20.39	20.44
45D	8.44	8.38	8.51	8.36	8.36	1.77	1.70	1.69	1.68	1.64	21.75	21.77	21.82	21.89	21.86

* Values listed are in millimeters.
** 2 SD = 0.22 millimeters.

TABLE C-2
ANCHORAGE DATA FOR PATIENT BM

TOOTH *	MESIO-DISTAL DAY 1	MESIO-DISTAL DAY 24	MESIO-DISTAL DAY 52	MESIO-DISTAL DAY 87	OCCLUSO-GINGIVAL DAY 1	OCCLUSO-GINGIVAL DAY 24	OCCLUSO-GINGIVAL DAY 52	OCCLUSO-GINGIVAL DAY 87	BUCCO-LINGUAL DAY 1	BUCCO-LINGUAL DAY 24	BUCCO-LINGUAL DAY 52	BUCCO-LINGUAL DAY 87
31	9.83	9.70	9.83	9.69	1.07	1.13	1.09	1.16	4.27	4.26	4.28	4.40
33	5.93	5.80	5.93	5.93	1.47	1.45	1.55	1.56	13.89	13.60	13.74	13.80
34B	1.89	1.94	1.89	1.89	0.07	0.13	0.15	0.16	18.23	18.26	18.32	18.30
34L	0.71	0.68	0.71	0.73	1.25	1.13	1.11	1.24	15.67	15.74	15.80	15.70
34D	0.37	0.42	0.37	0.37	0.53	0.51	0.53	0.56	18.17	18.26	18.32	18.30
35B	3.93	3.90	3.93	3.91	0.05	0.11	0.09	0.12	23.03	23.02	23.00	23.00
35L	5.77	5.84	5.77	5.81	0.15	0.17	0.11	0.12	18.23	18.26	18.14	18.18
35D	7.41	7.28	7.41	7.37	0.93	1.57	0.91	0.90	21.71	21.88	21.84	21.80
41M	10.67	10.72	10.67	10.69	0.95	1.01	0.99	1.02	0.13	0.22	0.28	0.30
41D	9.79	9.82	9.79	9.73	0.95	1.01	0.99	1.02	2.61	2.58	2.76	2.66
43	5.23	5.16	5.23	5.17	1.65	1.41	1.59	1.46	12.35	12.26	12.24	12.30
44B	0.77	0.92	0.77	0.79	0.17	0.23	0.37	0.30	16.81	16.88	16.82	16.84
44M	0.29	0.30	0.29	0.31	0.63	1.15	1.17	1.04	14.91	14.90	14.98	14.94
45B	6.15	6.12	6.15	6.13	0.05	0.11	0.09	0.12	19.21	19.22	19.24	19.24
45L	7.45	7.42	7.45	7.41	0.73	0.73	0.63	0.74	15.37	15.48	15.40	15.40
45M	4.29	4.28	4.29	4.25	0.93	0.95	0.87	0.84	17.01	17.00	16.98	16.94
45D	9.01	9.12	9.01	9.07	1.39	1.49	1.41	1.34	18.35	18.34	18.32	18.42

* Values listed are in millimeters.
** 2 SD = 0.22 millimeters.

TABLE C-3
ANCHORAGE DATA FOR PATIENT GH

TOOTH #	MESIO-DISTAL			OCCLUSO-GINGIVAL			BUCCO-LINGUAL		
	DAY 1	DAY 22	DAY 35	DAY 1	DAY 22	DAY 35	DAY 1	DAY 22	DAY 35
31M	10.79	10.79	10.80	2.23	2.25	2.28	2.34	2.15	2.18
31D	10.33	10.39	10.40	2.23	2.25	2.28	0.72	0.91	0.92
33	5.37	5.47	5.58	1.57	1.49	1.52	9.64	9.81	9.72
34B	0.43	0.53	0.50	0.43	0.43	0.46	13.48	13.55	13.62
34L	0.73	0.75	0.64	1.77	1.87	1.78	10.54	10.71	10.66
34D	1.89	2.05	2.10	0.93	1.03	0.88	13.34	13.39	13.42
35B	6.33	6.33	6.32	0.83	0.81	0.78	17.26	17.45	17.42
35L	8.67	8.67	8.56	1.61	1.57	1.68	13.46	13.57	13.56
35M	4.79	5.03	4.90	1.37	1.13	1.28	14.86	15.07	15.08
35D	8.87	8.85	9.00	2.77	2.95	2.82	18.32	16.33	16.32
41	11.29	11.19	11.10	2.65	2.63	2.54	7.14	6.97	6.98
43	4.17	4.17	4.18	2.13	2.15	2.18	18.48	18.29	18.32
44B	2.63	2.63	2.66	0.47	0.43	0.42	21.84	21.85	21.68
44L	3.11	3.14	3.08	1.23	1.15	1.22	18.94	18.95	18.88
44M	0.83	0.67	0.80	0.21	0.07	0.12	20.28	20.17	20.22
44D	4.55	4.45	4.54	1.03	1.01	1.08	22.54	22.45	22.44

* Values listed are in millimeters.
** 2 SD = 0.22 millimeters.