The effect of a transpalatal or Nance palatal arch on sliding mechanics with varying degrees of molar rotations

By

Emile Habib
BDS MJDF MOrth RCS (Eng)

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School of Dentistry
Birmingham Dental Hospital
Mill Pool Way
Birmingham
B5 7EG

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Abstract

Aims: To determine if the use of a transpalatal (TPA) or Nance palatal arch with varying degrees of molar rotations significantly affects resistance to sliding during sliding mechanics. Also, to establish if there is reduced resistance to sliding using the extraoral tube (EOT) on molar bands opposed to the straight wire tube when using a TPA or Nance palatal arch with rotated molars.

Materials and method: A custom made experimental apparatus approximating the transpalatal arch, allowing for 1-degree incremental changes to molar rotation was designed. A 0.019 x 0.025" stainless steel archwire was displaced through the molar tubes to determine the effect of molar rotation on resistance to sliding, determined as work. Unilateral and bilateral palatal rotations were evaluated as well as comparison of the extraoral and straight wire tube.

Results: The work required to achieve a constant archwire displacement was significantly increased for bilaterally, palatally rotated molars compared with a unilateral rotation ($p<0.05$ for displacement of both 0.5 and 0.1 mm). Pearson correlation analysis identified a significant association between extent of molar rotation and difference in work between unilateral and bilateral rotated molars (p-value 0.002 and 0.01 for displacement of 0.5 and 0.1 mm respectively). Placement of the archwire in the extraoral tube significantly reduced the work required for a fixed displacement compared with the straight wire tube. The magnitude of the effect was greatest for bilateral palatal rotated molars and was highly significant ($p<0.001$ for 0.5 mm) compared with a unilateral palatal rotated molar.

Conclusion: The relationship between work and molar rotation was found to be non-linear, with an exponential increase in work with increasing palatal rotations. Bilaterally, palatally rotated molars resulted in a significantly increased amount of work for all amounts of displacement of the archwire compared with a unilateral rotation. Use of the EOT significantly reduced the work required to displace the archwire compared with the straight wire tube.

Acknowledgements

I would like to dedicate this research project
to my Grandmother, who sadly passed away October 2016

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Chapter one: Literature review and aims of study

1.1 Introduction

Orthodontic tooth movement is based on the principal that when a force is applied to a tooth, it stimulates a reaction within the periodontium. Remodeling of the periodontal ligament and alveolar bone occurs and results in tooth movement. The first stage of orthodontic treatment is to level and align the dental arches. Leveling and alignment includes derotation of any teeth. The maxillary first permanent molars are commonly rotated. During derotation, mesial tooth movement is often undesirable, especially in a class II malocclusion. Should auxiliary appliances be used to prevent any mesial movement, the pre-treatment position of the maxillary first permanent molar is fixed and any rotations maintained during this phase of orthodontic treatment.

1.2 Rotated First permanent molars (FPMs)

The mandibular and maxillary first permanent molars erupt around 6.5 years of age (Berkovitz *et al.*, 2009), signifying the start of the mixed dentition stage of dental development. Malposition of first permanent molars can be a significant aetiological factor in malocclusion, as molar relationship is considered a key factor in achieving an ideal and stable occlusion. Angle (1899) based his classification of occlusion on molar relationship and upon examining the ideal occlusion, he determined that the mesiobuccal cusp of the upper first permanent molar should occlude with the sulcus between the buccal cusps of the lower first permanent molar (Angle, 1899). With the molars in this position, it is classified as a class I molar relationship. A Class II molar relationship occurs when the mesiobuccal cusp of the upper first permanent molar occludes anteriorly to this position.

With the first permanent molars in the ideal position, it results in good intercuspation of the upper and lower buccal dentition, adequate space anteriorly for overjet and overbite correction and creates a stable occlusion. Andrews (1972) described six key factors required in order to have an ideal static occlusion. One of the reported six keys of occlusion was molar relationship; "the distal surface of the distal marginal ridge of the upper first permanent molar occludes with the mesial surface of the mesial marginal ridge of the lower second molar. The mesiobuccal cusp of the upper first permanent molar falls within the groove between the mesial and middle cusps of the lower first permanent molar". Another key that Andrews (1972) described in the ideal occlusion was the absence of any rotations within the arches.

1.2.1 Quantifying degree of molar rotation

Palatal rotation of the maxillary first permanent molars has been described in the literature, especially in class II malocclusions (Friel, 1959;Hellman, 1920;Lamons and Holmes, 1961). Hellman (1920) reported a very high prevalence of mesio-palatal rotation of the maxillary first permanent molar. The palatal root of the maxillary first permanent molar is much larger than the two buccal roots. This longitudinal axis forms a pivotal point that can result in a rotation of the molar (Hellman, 1920). Several studies (Foresman, 1964;Friel, 1959;Hellman, 1920;Henry, 1956) have been conducted in order to evaluate the prevalence, direction and extent of molar rotation. All of the studies have found that the maxillary first permanent molar rotates in a palatal direction, with the mesiobuccal cusp displaced palatally.

Henry (1956) aimed to identify the optimum angle at which the molars would be ideally aligned within the dental arch. The degree of rotation of the molar was measured by the angle formed between the median raphe and a line through the buccal cusps of the molar. The study found that the optimum angle of the first permanent molar (angle of Henry) had a mean value of 11.2^0. Henry also agreed with previous work by Hellman (1920), reporting that the longitudinal axis of rotation was directed through the palatal root and mesiopalatal cusp. He concluded that mesiopalatally rotated maxillary first permanent molars were frequently observed, occurring in 83% of malocclusions (Henry, 1956). Due to this high prevalence rate, the rotation of the maxillary first permanent molar needs to be examined and accounted for during orthodontic treatment.

Friel (1959) carried out a similar study to Henry (1956) but used a different methodology. Using the median raphe as a reference plane, Friel measured the angle formed between this plane and a line through the mesiobuccal and mesiopalatal cusps of the maxillary first molars. Measurements were taken from study models with a class I buccal occlusion and a class II buccal occlusion. The mean angle in the class I group was 60^0 on the right and 57^0 on the left, compared with 52^0 on the right and 51^0 on the left. The post-normal group had on average 7 degrees more mesiopalatal rotation compared with normal group (Friel, 1959).

Whilst the studies by Henry (1956) and Friel (1959) were well conducted, the sample size was small. Due to natural shape of the maxillary arch, a small anteroposterior change in the position of the molar could have a significant effect on the degree of rotation measured. No statistical analysis was presented.

Lamons and Holmes (1961), using the angle of Friel, found mesiopalatal rotations of the maxillary first permanent molar occur in 95% of cases. The study concluded that the optimum angle of Friel was 61^0 with a standard deviation of 4^0. A similar study by Foresman (1964) aimed to determine the amount of space gained (as rotated teeth occupy a wider mesio-distal width) within the arch from correction of the rotation of the maxillary first permanent molar. The study also validated the previous literature on the optimum angle of Friel and reported the optimum angle was 60^0, which was in agreement to the results from the studies by Friel (1959) and Lamons and Holmes (1961). The maxillary first permanent molars in untreated cases, on average, were $10\text{-}11^0$ more mesiopalatally rotated (Foresman, 1964).

Lima *et al* (2015) aimed to evaluate the correlation between the severity of class II division 1 malocclusions and the degree of the mesiopalatal rotation of the maxillary first permanent molar. The results showed that the mean angle of Henry for the samples was 14.5^0, which is higher than the optimum angle for the maxillary first permanent molar suggested by Henry as their sample did not examine any molars with a class I molar relationship. The mean angle of Friel was 58^0, which was comparable with previous studies. Statistical analysis found a relationship between the angles of Henry and Friel and the severity of the class

II molar relationship (Lima *et al.*, 2015). This suggests that the degree of mesiopalatal rotation of the molar is proportional to the severity of the class II molar relationship. The results were not statistically significant for all 4 groups, suggesting that it is only applicable to more severe class II molar relationships (Lima *et al.*, 2015). In clinical scenarios with a severe class II molar relationship where prevention of further mesial movement of the molar teeth is needed, the molars are likely to be rotated with an unknown effect on the sliding of the archwire through the molar tube if a transpalatal arch is used.

Lime *et al* (2015) presented a sample size calculation using 5 % alpha error and a power calculation with a correlation coefficient of 0.20. This differed from previous literature regarding quantifying molar rotations as no statistical analysis has been presented, if any were performed at all. As a result, this limits the quality of evidence provided by these studies. The main limitation of all the available literature is the small sample sizes. The angles and the differences between the angles evaluated were small, requiring a large sample size to have any statistical weighting and provide conclusive epidemiological results. Another limitation of the previous literature is some results were reported to two decimal places, an accuracy that could not have been reliably achieved.

In conclusion, rotated maxillary first permanent molars are frequently observed in class II malocclusions. The molar rotates in a palatal direction around the long axis of the palatal root and mesiopalatal cusp (Hellman, 1920;Henry, 1956). Friel suggested molars in a class II relationship were, on average, 7^0 more mesiopalatally rotated (Friel, 1959). Other studies have found comparable results, with Foresman (1964) reporting molars of class II malocclusion on average 10-11^0 more mesiopalatally rotated. A recent study has identified a proportional relationship between the degree of molar rotation and the severity of the class II molar relationship (Lima *et al.*, 2015). In cases deemed to be of high anchorage demand, due to the molars already being in a class II molar relationship, it can be assumed that the molars will frequently be mesioplatally rotated. Use of anchorage reinforcement in the form of a trans-palatal or Nance palatal arch without prior de-rotation of the molars, could have detrimental effects on the mechanics of the orthodontic fixed appliance and, as a result, prevent orthodontic tooth movement.

1.3 Orthodontic fixed appliances

With the development and evolution of enamel bonding and machine milled brackets, most orthodontic treatment is now carried out using fixed appliances. Edward Angle first described the edgewise appliance in 1928 (Angle, 1928). He introduced a machine-milled bracket, which in combination with a rectangular archwire and wire bending allowed for control of tooth movement in all three planes; in/out, tip and torque. In 1976, Andrews introduced the pre-adjusted edgewise appliance, called the Straight Wire Appliance (Andrews, 1976; 1979). The brackets were precisely milled to incorporate a specific in/out, tip and torque value per tooth, reducing the amount of wire bending required. The prescription of the bracket was based on the scientific study of 120 non-orthodontic patients deemed to have an ideal occlusion (Andrews, 1972).

Since the introduction of the pre-adjusted edgewise appliance, numerous different prescriptions have become available. Andrews originally introduced different bracket prescriptions for extraction and non-extraction cases to account for the different treatment mechanics required, as well as different prescriptions depending on the amount of crowding present (Andrews, 1979). To simplify the inventory of brackets, orthodontists have suggested a single bracket prescription that could be used and modified for most cases. McLaughlin, Bennett and Trevisi (1990) introduced the most commonly used prescription in the UK, the “MBT” prescription. Several modifications to the prescription originally described by Andrews were made. The prescription reduced the tip in the maxillary buccal segments, in order to reduce the anchorage demands (Mclaughlin and Bennett, 1990). Increased mesial tip would put more strain on the anchor teeth when trying to bodily retract the labial segment, resulting in anchorage loss with the anchor teeth moving mesially.

The pre-adjusted edgewise appliance has revolutionized modern day orthodontics. The appliance system has reduced chair-side time due to the reduced need for wire bending. It allows for control of tooth movement in all three planes and provides precise, detailed finishing of cases. The system utilizes sliding mechanics (Andrews, 1976) which allows the clinician to use a variety of different biomechanics to achieve the desired tooth movements. Sliding mechanics means a bracket can slide along an archwire or an archwire can slide through the bracket or molar tube. Although it has created a larger variety of mechanics that can be used, it has the disadvantage of the inherent issue of friction. This is the main disadvantage of the pre-adjusted edgewise appliance.

Tooth movement is resisted as a result of the friction that occurs between the brackets, archwire and ligature interface. As a result of this increased frictional force, the pre-adjusted edgewise appliance is more anchorage demanding than other appliance systems that do not use sliding mechanics, for example, the Begg appliance (Begg, 1956). These increased anchorage demands create a need for anchorage reinforcement to limit anchorage loss, which manifests in the form of undesired tooth movement. In a class II malocclusion this is usually the mesial movement of the maxillary buccal segment.

1.4 Friction

By sliding an orthodontic bracket along an archwire, the sliding movement results in a frictional resistance that can hinder or even prevent tooth movement. With the widespread adoption of the pre-adjusted edgewise appliance, understanding of frictional resistance, its magnitude and clinical significance is critical (Tidy, 1989).

Friction is the force that resists the relative motion of two objects in contact with one another. The direction of the force is tangential to the two surfaces in contact (Drescher *et al.*, 1989). Stoner (1960) first documented the significance of friction in orthodontics when he recognized that orthodontic appliance inefficiency resulted in an applied force being dissipated by friction or improper application. Clinically, this creates difficulty in controlling the amount of force delivered to individual teeth (Stoner, 1960). The direction of the force from frictional resistance occurs in the opposite direction to the moving object. Therefore it is essential that frictional forces should be minimised or completely eliminated when tooth movement is desired (Drescher *et al.*, 1989), otherwise frictional resistance can prevent tooth movement and/or result in anchorage loss (undesired tooth movement) (Edwards *et al.*, 1995). Using appliances and mechanics that have low frictional resistance has the added potential benefit of reducing the overall treatment time.

1.4.1 The laws of friction

To comprehend the relevance and implications of frictional resistance with orthodontic tooth movement, it is important to understand the so-called classical laws of friction (Amontons, 1699):

1. Frictional force is proportional to the applied load, that is the force normally acting on the object. In orthodontics this law is obeyed by all force couples.
2. The coefficient of friction is independent of the surface area in contact.
3. The coefficient of friction is independent of the sliding velocity. With materials that move with a repeated stop-start motion, as occurs with orthodontic tooth movement, this law would only be obeyed if the optimal sliding velocity and its implementation were known. Therefore this law is not obeyed during the clinical practice of orthodontics.

(Amontons, 1699;Jastrzebski, 1976;Kusy and Whitley, 1997)

1.4.2 Types of friction

There are two types of frictional resistance forces that occur during the relative motion of two solid surfaces in contact. These two frictional forces can be defined as two separate entities (Omana *et al.*, 1992):

1. Static friction – The smallest force required to initiate movement of two solid surfaces in contact that were previously at rest.
2. Kinetic friction – The force that resists the sliding motion of two solid surfaces in contact once movement has started.

Static friction is generally greater than kinetic friction as it is more difficult to change an object from a state of inertia than to maintain its movement once initiated (Kapila *et al.*, 1990;Nanda and Ghosh, 1997;E. P. Rossouw, 2003). In orthodontic tooth movement both static and kinetic friction are important and are dynamically related (P. E. Rossouw *et al.*, 2003). For a given normal force (N), the drawing force (F) builds up to a maximum point (F_{max}) before a sudden drop in the drawing force occurs. The drawing force drops to a relative plateau. The maximum drawing force equates to the coefficient of static friction and the coefficient of kinetic friction is defined by the plateau phase (Kusy and Whitley, 1997). According to the laws of physics, the area under the plateau is the work involved to maintain motion (kinetic friction).

1.4.3 Resistance to sliding

Orthodontic tooth movement does not occur in a smooth, continuous motion along the archwire but in a sequence of short steps (Frank and Nikolai, 1980;Prashant *et al.*, 2015). The tooth alternates between tipping of the crown and subsequent uprighting of the root. The application of force to the tooth creates a moment on the tooth crown, resulting in tipping of the crown in the direction of the force. As the tooth tips the archwire binds against the edge of the bracket (binding). This binding results in an increase in the frictional resistance and restricts tooth movement (Chimenti *et al.*, 2005;Drescher *et al.*, 1989;Kusy and Whitley, 1997;Read-Ward *et al.*, 1997). Consequently, static friction affects space closure more than kinetic friction (Omana *et al.*, 1992) but is inherently more difficult to simulate and consistently measure.

Friction is only one of the factors that can affect the resistance of sliding of a bracket along a wire or a wire within a molar tube. Kusy and Whitley (1999) defined three factors that affect resistance to sliding:

1. Friction – As a result of contact between the wire and bracket surface. This can be static or kinetic friction.
2. Binding – This occurs when the tooth tips or the archwire flexes under loading and contact occurs between the wire and the corners of the bracket.
3. Notching – This is the permanent deformation of the wire that occurs when the wire contacts the bracket corner above the critical angle. The notching deforms the wire by gouging out microscopic areas on its surface. Notching prevents tooth movement completely until the notch is released. (Kusy and Whitley, 1999)

Burrow (2009) defined how friction, binding and notching affected the resistance to sliding by considering the three phases that occur during orthodontic tooth movement:

1. First phase – Resistance to sliding = Frictional resistance + Binding

   During the initial phase of tooth movement, the crown of the tooth tips and contact between the wire and bracket corner begins. Both friction and binding are factors that affect the resistance to sliding in this phase.

2. Second phase – Resistance to sliding = Binding

   During this phase binding is the main factor that affects resistance to sliding because as the tooth continues to tip, the contact angle between the wire and bracket increases further resulting in greater binding. Friction is not a major factor during this phase.

3. Third phase – Resistance to sliding = Notching

   As the contact angle between the bracket and wire continues to increase, notching will occur above a certain angulation. These notches on the wire lock into the bracket corner and prevent tooth movement until released. The affect of friction and binding in this phase are minor.

(Burrow, 2009)

1.4.4 Friction and Anchorage

The literature on friction in orthodontics indicates that in order to overcome it and achieve tooth movement higher forces are required. There is a belief that these greater force levels increase the strain on the anchor teeth and have the potential for anchorage loss. As a result, orthodontists consider anchorage reinforcement with auxiliary appliances or mechanics with reduced friction to minimise this risk.

One method for anchorage control would be to concentrate the applied orthodontic force to the teeth that require movement, and dissipate the resultant reactionary forces over as many teeth as possible. This may result in the applied force being dissipated over a larger, cumulative root surface area and reduce the potential for movement of the anchor teeth. Profitt *et al* (2012) has proposed a theoretical relationship of tooth movement to the pressure within the periodontal ligament. As the orthodontic force is applied to the desired teeth to be moved, pressure in the periodontium results in a biological response eliciting remodeling of the periodontal ligament and alveolar bone. This results in tooth movement. Pressure in the periodontal ligament equates to the force applied to a tooth divided by the surface area of the periodontal ligament that the force is dissipated over. As the force levels increase, the pressure within the periodontal ligament increases and tooth movement occurs. A threshold level exists for the optimum force required to maximise tooth movement. Below this threshold there are minimal reactionary forces on the anchor teeth and although the amount of desired tooth movement is not optimal, tooth movement does occur. Above this threshold a relative plateau exists where higher forces do not result in increased tooth movement (Quinn and Yoshikawa, 1985). As the force levels and resulting pressure in the periodontal ligament increases further, the amount of desired tooth movement decreases and there is an increase in the reactionary forces on the anchor teeth. With these high force levels the anchor teeth may move more than the desired teeth, as the forces are too high to move the desired teeth but are in the optimum range for the anchor teeth (Figure 1.1). (Proffit *et al.*, 2012;Quinn and Yoshikawa, 1985)

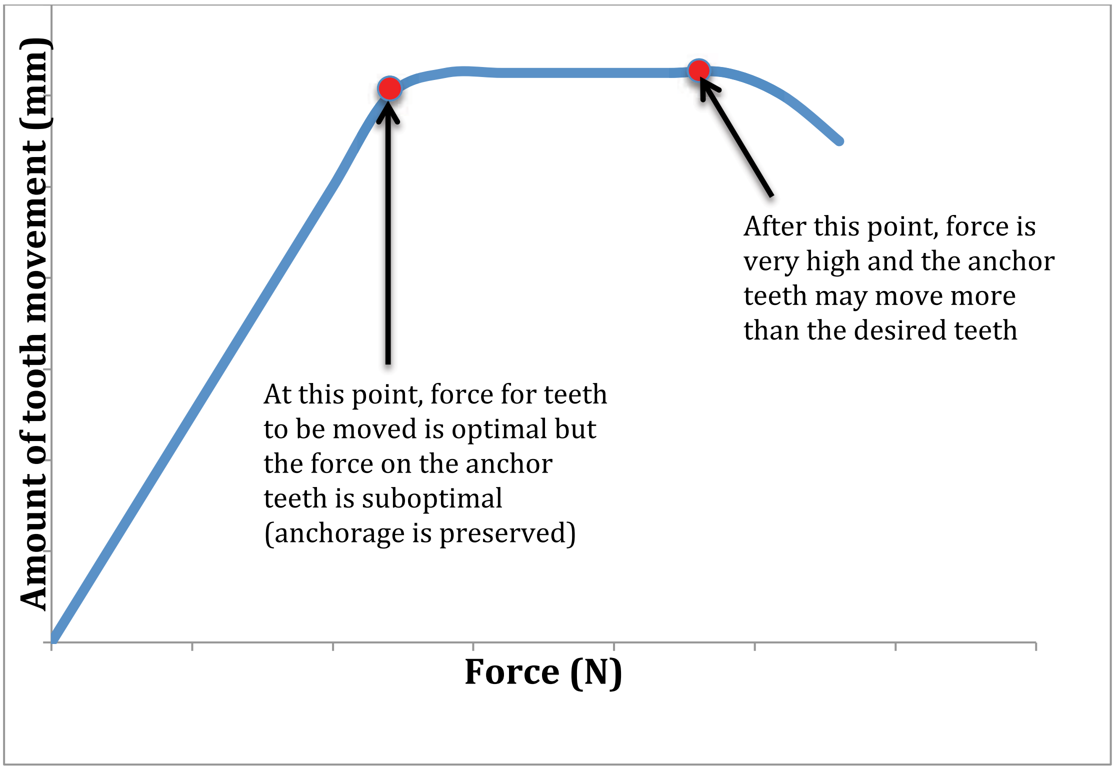

Figure 1.1 Graphical representation of the relationship between tooth movement and applied orthodontic force

1.4.5 Factors affecting friction

The aetiology of frictional resistance in orthodontic appliances is multi-factorial, with complex interactions between the various factors (Rock and Wilson, 1989), and it is difficult to predict the frictional resistance in different bracket/archwire combinations (Sims *et al.*, 1994). The factors affecting friction in orthodontics are:

- Archwire – material, cross-sectional shape and stiffness
- Bracket – material, width, inter-bracket distance and prescription
- Archwire/bracket interaction - ligation
- Biological factors – the main factors are saliva and occlusal forces

Although these factors are not tested in this study, their complex interaction needs to be considered. Clinically these variables will affect friction significantly and will vary between patients. Laboratory based studies can therefore provide an approximation of in-vivo behavior or be used to study a narrow selection of potential variables to contribute to our mechanistic understanding of appliance behavior.

1.4.6 Archwire material

Orthodontic archwires are fabricated from different substrates and may be presented with different surface coatings. Differences in frictional resistance between archwire materials including Nickel Titanium (NiTi), Elgiloy wires and stainless steel (SS) wires have been demonstrated (Drescher *et al.*, 1989;Frank and Nikolai, 1980;Kusy and Whitley, 1999). Frictional resistance may be modified by changing the surface finish of the archwire through machining, coating or ion implantation (Kapila *et al.*, 1990;Kusy *et al.*, 2004).

1.4.7 Archwire cross-sectional shape and stiffness

Orthodontic archwires can be round, square or rectangular in cross-section and clinicians use the varying cross-sectional shapes according to the required tooth movements and desired three-dimensional control. There is evidence to support that rectangular archwires produce more friction than round archwires (Tidy, 1989) but research has suggested that it is the occluso-gingival dimension of the archwire that is the most important factor (Drescher *et al.*, 1989;Frank and Nikolai, 1980).

1.4.8 Bracket material

Stainless steel brackets and molar tubes are the most popular choice of bracket material in orthodontics and have been found to permit significantly more tooth movement than ceramic brackets (Tanne *et al.*, 1991). The mean frictional forces with stainless steel brackets and four different wire alloys (SS, cobalt-chromium, NiTi and β-titanium) have been found to range between 40 and 336 g (Kapila *et al.*, 1990).

1.4.9 Bracket width and inter-bracket distance

The bracket width is defined as the mesio-distal width of the bracket slot. The different critical angles formed between narrow and wide brackets explain the different levels of friction experienced (Tidy, 1989). Narrow brackets allow more tipping before the critical angle is reached at the bracket/archwire interface (Drescher *et al.*, 1989). The greater the critical angle the greater the frictional resistance (Andreasen and Quevedo, 1970).

There is limited published literature available on the effect of inter-bracket distance on friction. Some studies have reported no effect from inter-bracket distances on friction (Frank and Nikolai, 1980), whilst others have shown that reduced inter-bracket distance increases binding (Kusy and Whitley, 2000).

1.4.10 Bracket prescription

The pre-adjusted edgewise appliance revolutionised orthodontics by incorporating first, second and third order adjustments specific to each tooth, as well as permitting sliding mechanics. First order adjustments account for the varying in-out requirements per tooth to achieve alignment. Second order adjustments vary the tip (angulation) and third order accounts for the different torque (inclination) required for each tooth. The various prescriptions available incorporate different amounts of first, second and third order adjustments, with each adjustment having a relatively unknown effect on frictional resistance.

With mild second order adjustments, the slope of the archwire within the bracket slot results in minimal contact at the mesial or distal edge of the bracket corner. For brackets with increased tip, the archwire contacts the opposing edges of the bracket slot diagonally. This results in a greater amount of binding and therefore an increase in the frictional resistance (Frank and Nikolai, 1980;Kusy and O'Grady, 2000;Loftus *et al.*, 1999;Peterson *et al.*, 1982;Tidy, 1989;Tselepsis *et al.*, 1994). Sims *et al* (1994) reported a linear relationship between increasing the tip and torque of the bracket prescription and the associated increase in friction.

Third order adjustments allow three-dimensional control of the tooth root position. Numerous studies have investigated the effect of tip (angulation) and torque (inclination) on frictional resistance with the pre-adjusted edgewise appliance. All of the studies have concluded that increases in bracket tip produced a significant increase in friction, as did torque but to a lesser extent (Frank and Nikolai, 1980;Kusy and O'Grady, 2000;Loftus *et al.*, 1999;Peterson *et al.*, 1982;Tidy, 1989;Tselepsis *et al.*, 1994).

To date there have been no previous studies investigating the relationship of rotated teeth and its effect on resistance to sliding. Correction of rotated teeth is carried out during the leveling and aligning stage at the start of treatment. A unique scenario arises when the maxillary first permanent molars position is fixed at the start of treatment when using a transpalatal or Nance palatal arch. The aim of this proposed study is to investigate the effect molar rotation has on resistance to sliding.

Studies investigating the effect of tip and torque on frictional resistance used a specially constructed jig that allowed for 1-degree variations in the tip and torque between the bracket and archwire. The jigs varied from a single bracket to a full arch model, mounted securely in an Instron tension-testing machine. The different methodologies between the studies allows only for relative comparison (Frank and Nikolai, 1980, Kusy and O'Grady, 2000, Loftus et al., 1999, Peterson et al., 1982, Tidy, 1989, Tselepsis et al., 1994).

1.4.11 Ligation

The frictional force exerted by a ligature is dependent upon its coefficient of friction and the force it exerts on the archwire to engage it into the bracket slot (Franco *et al.*, 1995). Iwasaki *et al* (2003) concluded that 31-54 % of the total intra-oral frictional force was due to ligation when a premolar bracket was moved along a 0.019 x 0.025” SS archwire.

As the archwire is enclosed within a molar tube, no method of ligation is required. The behavior of the tube can be expected to perform in a similar manner to self-ligating brackets, as it is a stainless steel archwire within a stainless steel tube. Interestingly, as far as the author is aware, no studies have been published evaluating the effect of tube length on frictional resistance and binding of the archwire.

1.4.12 Biological factors – Saliva and occlusal forces

The effect of the oral environment on sliding mechanics has been widely debated with literature providing contrasting evidence. Clinically, biological variation between patients effects friction differently and is a significant factor that cannot be easily replicated in laboratory studies. The two main factors that have to be considered are saliva and occlusal forces. Occlusal forces, especially during mastication, vary significantly between patients and are significantly larger than those applied to the teeth by the orthodontic appliance. Its effect varies significantly between patients and is difficult to replicate in laboratory-based studies.

1.5 Anchorage

In orthodontics anchorage is defined as the resistance to reactionary forces, or the prevention of unwanted tooth movement. Newton's third law of motion states that all forces acting between two objects are of the same magnitude but are opposite in direction. Orthodontic tooth movement is achieved by applying force to teeth via an orthodontic appliance. When a force is applied to move teeth in a particular direction, it results in an equal force being exerted in the opposite direction. This creates the potential for undesired tooth movement, also referred to as anchorage loss (Proffit *et al.*, 2012). These reciprocal forces must be considered during treatment planning and adequate methods used to control these forces during treatment so that the occlusal objectives at the end of treatment can be achieved.

1.5.1 Principles of anchorage

According to the differential force theory (Begg, 1956), orthodontic tooth movement is related to the force per unit root surface area. Research has shown that teeth with a greater root surface area have increased resistance to tooth movement, or increased anchorage value (Hixon, 1970). However, the relationship that exists between root surface area and tooth movement is non-linear, suggesting other factors also have a significant contribution to tooth movement (Pilon *et al.*, 1996). As previously discussed, tooth movement increases with an increased applied force until the optimum force is reached. Thereafter an increase in force does not result in a greater amount of tooth movement, only an increased strain on the anchor units (Quinn and Yoshikawa, 1985).

Clinically, the orthodontist aims to dissipate the reactionary forces over as many teeth as possible to limit the potential for unwanted tooth movement. Heavy forces should be avoided and ideally forces kept as low as possible to avoid any anchorage loss and movement of the anchor teeth. Restricting these teeth to bodily movement can increase the anchorage value of the anchor teeth further, as larger forces are required to move teeth bodily.

1.5.2 Sources/types

There are numerous potential sources for anchorage reinforcement, either intraoral or extraoral. The extraoral source of anchorage is achieved with the use of headgear, whether conventional or protraction headgear. Anchorage is gained by using the cranial vault or the basal bones to oppose the orthodontic forces applied to teeth. Intraoral sources of anchorage can be gained from teeth, soft-tissues or bone.

1.5.3 Intraoral anchorage – teeth

Teeth are the most commonly used form of intra-oral anchorage. When applying force to a tooth against another tooth in order to induce tooth movement, it is classified as simple anchorage. When there is more than one tooth in the anchor unit (Moyers, 1973), it is classified as compound anchorage. This can be achieved from an intra- or inter-maxillary (with the use of elastics between opposing arches) source (Quinn and Yoshikawa, 1985).

1.5.4 Intraoral anchorage – Soft tissue/Bone

The soft tissues, in terms of the oral musculature, also provide anchorage and resistance to unwanted tooth movement, or even exert active forces to produce tooth movement (Cetlin and Hoeve, 1983).

Cortical anchorage results because cortical bone is more resistant to resorption than medullary bone, providing greater resistance to tooth movement when in contact with the roots of teeth (Hixon, 1970;Ricketts, 1979). Cortical anchorage can be utilized clinically with the use of certain mechanics. However, there is no scientific evidence available to support the concept of cortical anchorage (Stivaros *et al.*, 2010) and is based on clinical experience. For example, by applying buccal root torque to posterior teeth to bring the roots of the teeth into contact with the cortical plates, it is believed that the mesial movement of these teeth is reduced but there is an increased risk of root resorption. It has been suggested that a transpalatal arch is a form of cortical anchorage. The reactionary forces on molar teeth result in mesially directed tooth movement, but by fixing the molar width the roots contact the cortical plates as the dental arch narrows anteriorly and inhibits further mesial movement.

Anchorage may be gained from alveolar bone via the use of temporary anchorage devices (TADs), osseointegrated dental implants or bone anchors to provide absolute anchorage (Ismail and Johal, 2002;Young *et al.*, 2007) and occasionally, even from ankylosed teeth (Kokich *et al.*, 1985).

Anchorage from basal bones is achieved when an appliance has palatal coverage. The anchorage is derived from the basal bone of the hard palate to provide resistance against which teeth can be moved. Examples include a removable appliance with palatal coverage or a Nance palatal arch, were an acrylic button joined to the upper first permanent molars via a stainless steel wire rests against the vault of the palate.

1.5.5 Transpalatal and Nance palatal arch

A transpalatal arch is an auxiliary appliance that consists of a stainless steel wire, usually 0.9 mm in diameter, that transverses the hard palate and is cemented to the maxillary first permanent molars via molar bands. It increases the anchorage value of the molar teeth by fixing the maxillary inter-molar width. It is believed to provide cortical anchorage by preventing the mesial movement of the molar teeth into a narrower part of the maxillary arch. The most commonly used design is the Goshgarian palatal arch (figure 1.2)(Goshgarian, 1972).

Fig 1.2: The Goshgarian transpalatal arch – 0.9 mm stainless steel wire is contoured to the shape of the palate and is soldered to molar bands. The incorporation of a U-loop in the midline increases flexibility of the wire to allow for correct placement of the appliance

Transpalatal arches are most commonly used in their passive form in order to reinforce anchorage. They can also be active and enable tooth movement (Stivaros *et al.*, 2010). A number of different tooth movements have been described in the literature, such as derotation of rotated molars (Cooke and Wreakes, 1978;Dahlquist *et al.*, 1996;Hoeve, 1985;Ingervall *et al.*, 1996), correction of molar crossbites (Ingervall *et al.*, 1995) and torqueing of the roots of the maxillary molars (Baldini and Luder, 1982).

A Nance (Nance, 1947), or Nance-button, palatal arch consists of a stainless steel wire that extends anteriorly along the hard palate and incorporates an acrylic button that lies on the palatal vault (figure 1.3). This provides anchorage in a similar manner to a transpalatal arch but it also utilises anchorage from the basal bone of the hard palate.

Figure 1.3: The Nance palatal arch – 0.9 mm stainless wire is contoured to the shape of the palate, extending anteriorly from the molar bands to the palatal vault. Overlying the vault of the palate, an acrylic button is added to provide anchorage from the basal bone of the hard palate.

The currently available literature is limited with a few clinical trials and laboratory-based studies on the biomechanical aspects and clinical management of transpalatal arches.

1.5.6 Evidence to support TPA or Nance palatal arch

A randomised clinical trial comparing the effectiveness of a Goshgarian and Nance palatal arch in preventing mesial drift, distal tipping, mesio-palatal rotation and patient comfort found no overall statistical or clinical advantage to provide scientific evidence for the use of one over the other (Stivaros *et al.*, 2010). Forty-nine that were treated with upper and lower fixed appliances, upper premolar extractions and either a Goshgarian or Nance palatal arch were included in the data analyses. Study models were digitally scanned and compared between pre-treatment and six-months into treatment following only leveling and aligning. No statistically significant difference in the average mesial movement of the upper first molar was found, with the mean for the Goshgarian and Nance palatal arch being 0.98 mm and 0.72 mm respectively. Statistically, the Goshgarian palatal arch was significantly better at preventing mesio-palatal rotation of the upper first permanent molars. The Nance palatal arch was reported to be significantly more uncomfortable by patients (Stivaros *et al.*, 2010). The trial may have benefitted from a control group, who received no palatal arch, in order to evaluate the effectiveness of each appliance in preventing mesial movement of the molars and reinforcing anchorage.

Zablocki *et al* (2008) undertook a cephalometric study to evaluate the effectiveness of a transpalatal arch in reinforcing anteroposterior and vertical anchorage. Using two non-randomised, matched groups they found that a transpalatal arch had no significant effect during extraction treatment. The transpalatal arch group had on average 0.4 mm less mesial and vertical movement of the maxillary first permanent molar, which was not clinically significant. In terms of health economics, the use of only a transpalatal arch for anchorage reinforcement is difficult to justify. This was in agreement with another investigation that reported loss of anchorage with the use of a transpalatal arch (Radkowski, 2007). The major limitation of this study was that lateral cephalogram radiographs were used to evaluate mesial movement of the upper molars. Linear measurements from these radiographs were variable and the study reported findings to 1-decimal place.

Mini-screw implants or temporary anchorage devices (TADs) are an increasingly popular method of anchorage reinforcement, despite a lack of conclusive, scientific evidence with regards to their effectiveness. The mini-titanium screws do not osseointergrate but rely on mechanical retention once in-situ to provide anchorage from the jaw bones. A recent Cochrane review has reported some moderate evidence is available to suggest TADs are effective in reinforcing anchorage compared with more conventional methods (Jambi *et al.*, 2014).

A multicenter, randomised clinical trial evaluated the effectiveness of three methods of anchorage reinforcement; a Nance palatal arch, headgear and TADs. Seventy-eight patients participated in the study, which found no difference between the methods in terms of anchorage reinforcement. A Nance palatal arch was perceived to be as equally comfortable as TADs but occlusal outcomes, as measured by the Peer Assessment Rating (PAR), were significantly better with TADs (Sandler *et al.*, 2014). It could be argued that the occlusal outcome is more dependent on the orthodontists' clinical skills and experience than the method of anchorage reinforcement. Currently, this is the most robust clinical research available with regards to method of anchorage reinforcement. However, it is not in agreement with other research. A previous randomised clinical trial reported significantly greater mesial movement of the maxillary first molars with a TPA than with TADs (Sharma *et al.*, 2012).

In summary, Goshgarian and Nance palatal arches are equally effective in reinforcing anchorage. There is a lack of evidence to support the use of these appliances for anchorage reinforcement, but no clinical trials have included a control group without any anchorage support to evaluate the overall effectiveness of these palatal arches. A recent randomised clinical trial (Sandler *et al.*, 2014) has found that a Nance palatal arch is as equally effective as TADs, and currently, TADs are perceived to be the best method of anchorage reinforcement, other than osseointergrated implants or bone anchors.

1.6 Aims and objectives of study

Aims:

- Determine if the use of a transpalatal (TPA) or Nance palatal arch with varying degrees of molar rotations significantly effects resistance to sliding during sliding mechanics
- Establish if there is reduced resistance to sliding using the extraoral tube (EOT) on molar bands as opposed to the straight wire tube when using a TPA or Nance palatal arch with rotated molars

Objectives:

1. Establish the range of molar rotations encountered from a randomly selected sample of patient study models
2. Identify whether varying degrees of molar rotation increases the kinetic friction required to allow the arch wire to slide through the straight-wire tube on the molar bands
3. Examine whether using the extraoral tube on molar bands alters the frictional force when using sliding mechanics in comparison to the straight-wire tube
4. Establish how the varying degrees of molar rotation would affect the efficiency of the sliding mechanics used in the pre-adjusted edgewise appliance

Chapter Two

Materials and Methods

Chapter Two: Materials and Methods

2.1 Estimating range of average molar rotations based upon ex-vivo data

Studies examining the degree of molar rotations present in class II malocclusions have concluded that the maxillary first permanent molar is mesio-palatally rotated on average by 7 to 11^0 (Foresman, 1964;Hellman, 1920). The parameters used in previous studies to examine the effect of angulation (mesio-distal angle) or inclinations (bucco-palatal angle) have ranged from 0 to 13^0 for angulation and 0 to 12^0 for inclination (Articolo and Kusy, 1999;Hamdan and Rock, 2008;Moore *et al.*, 2004). Although the parameters used in these studies can serve as a guide to the parameters for the present study, they are insufficient in order to form the parameters for this study, because the studies had small sample sizes and their cohort of malocclusions may be significantly different. No literature is available regarding the effect of rotated teeth on the resistance to sliding in the pre-adjusted edgewise appliance.

The range of average molar rotations for this study were estimated by measuring the angle of Friel and the angle of Henry on 50 randomly selected study models (Figure 2.1) from the Birmingham Dental Hospital model box storage room. No previous studies were available to guide sample size calculations. However, by examining the left and right molar independently, 50 study models would give a large sample size of 100 models which was felt to be sufficient. The purpose of this exploratory study was to identify a range of clinically relevant first permanent molar angulations for subsequent in-vitro simulations and not specifically to allow generalization of epidemiological data to a larger population. A random number generator (www.randomizer.org) was used to select the study models from the database. The study models were scanned at a resolution of 9600 x 4800 dpi, using an Epson flatbed scanner and subsequently printed at 300 dpi (figure 2.1).

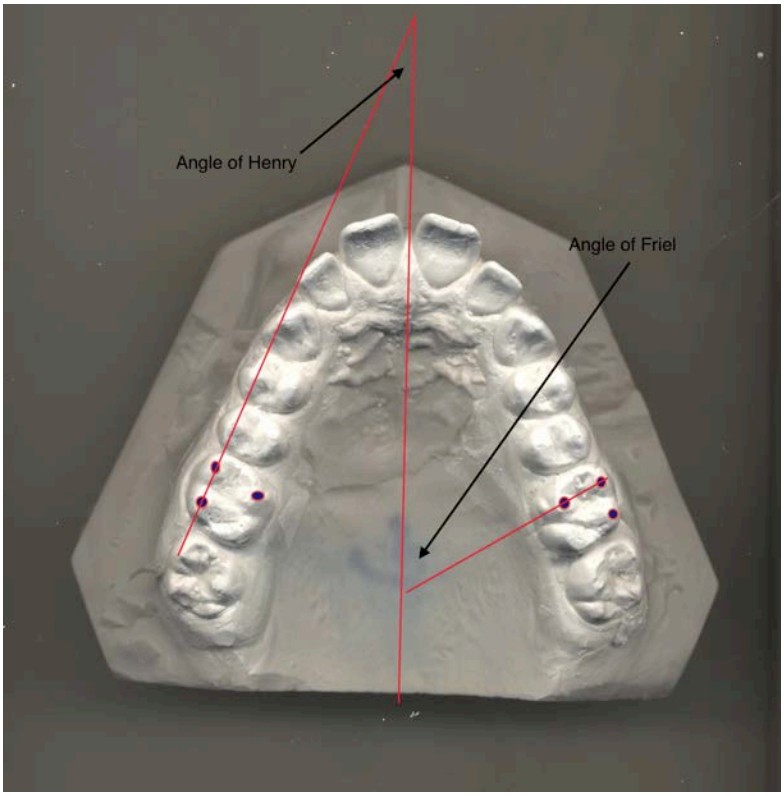

Figure 2.1: Example of scanned study model and illustration of the angles of Friel and Henry

From the printed images, anatomical points (Table 2.1) were identified and clearly marked with a 0.1 mm fibre-tipped pen to serve as reference for the lines and angles to be measured. These angles were measured by hand using a protractor and used to evaluate the degree of molar rotation. The various points, lines and angles measured are listed in Table 2.1.

Table 2.1: Anatomical points, reference lines and angles measured from study models

Points	
R1	Most anterior point of the palatal raphe
R2	Most posterior point of the palatal raphe
MP	Tip of the mesio-palatal (MP) cusp of the maxillary first permanent molar
MB	Tip of the mesio-buccal (MB) cusp of the maxillary first permanent molar
DB	Tip of the disto-buccal (DB) cusp of the maxillary first permanent molar
Lines	
R1-R2	Line connecting points R1 to R2
MB-DB	Line connecting points MB to DB
MB-MP	Line connecting points MB to MP
Angles	
Angle of Friel	Angle between the palatal raphe and the line MB to MP
Angle of Henry	Angle between the palatal raphe and the line MB to DB

A single examiner (Emile Habib) measured the angles proposed by Henry and Friel to calculate the degree of rotation of the maxillary first permanent molar. To evaluate intra-examiner error, 20 % of the sample size was randomly selected and measurements repeated 120 days after the first measurements and compared with the original measurements. The angles obtained were examined by calculating the mean and standard deviation for the left and right molars, along with a 95 % normal range.

The results obtained from the assessment of a random sample of the orthodontic population at Birmingham Dental Hospital were then used to define in-vitro simulations to evaluate the effect of rotated molars on resistance to sliding in the transpalatal and Nance palatal arch set-ups.

2.2 Design of experimental apparatus

A specially designed apparatus (Figure 2.2) was used to measure resistance to sliding between a 0.019 x 0.025" inch stainless steel archwire (Resilient Orthoform III Ovid, 3M Unitek) and two stainless steel molar tubes fixed in position to replicate the effect of a transpalatal arch. This archwire size was selected, as it is the most commonly used working archwire in clinical practice. The apparatus allowed for the molar tubes to be precisely rotated buccally or palatally in 1-degree increments. The design of the experimental jig was adapted from previous studies (Hamdan and Rock, 2008;Moore *et al.*, 2004).

The apparatus was set-up on a 300mm x 300mm solid aluminum base plate (High Density Mini-Breadboard MS12B, Thorlabs, Inc). The base plate weighed 2.37 kg to provide stability for mounting of 2 rotational stages (Mini-series rotation platform MSRP01, Thorlabs, Inc). The stages were mounted and fixed to the base plate on stainless steel rods at the average inter-molar width of 51mm (Bishara *et al.*, 1997). This recreated the effect of a transpalatal arch by fixing the molar tubes in an antero-posterior direction.

To the rotation stage a lab fabricated, cast metal head was fixed in place. It was grooved to allow for the molar bands (MBT™ prescription, Victory series™, 3M Unitek) to be changed and secured in an identical position. The molar tubes were aligned so that when at 0^0 rotation the archwire sat passively in both left and right molar tubes, following the natural curvature of the dental arch.

Testing was performed on a MTS universal test machine (Model 42, MTS Criterion® Series 40 Electromechanical universal test systems, MTS systems corporation, Minnesota, USA) using a 250 N load cell, recording the drawing force at 0.1-second intervals. The test apparatus was fixed to the lower clamp of the machine and the archwire secured to the upper clamp. The apparatus was positioned so that the archwire was moved only in a vertical direction relative to the molar tubes, therefore ensuring no tip or torque was introduced (Figure 2.2-2.4).

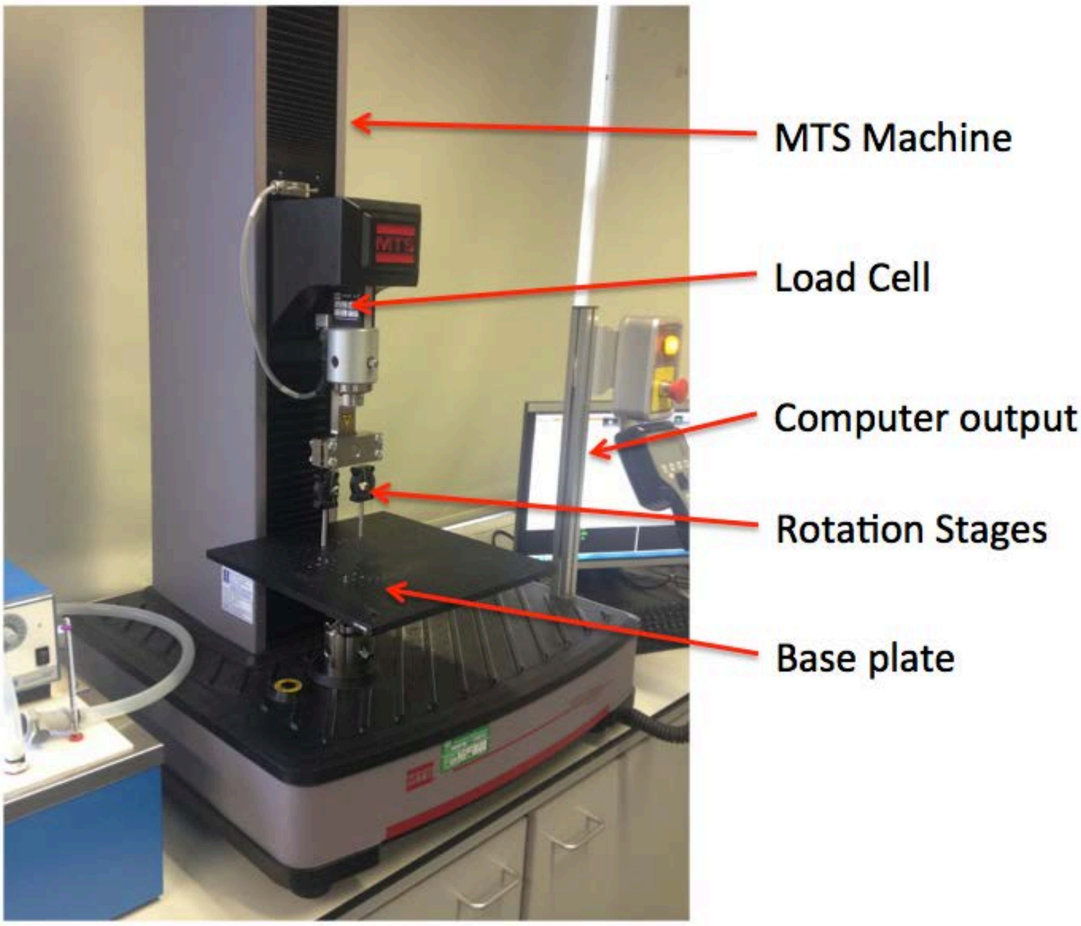

Figure 2.2: Test apparatus – overview

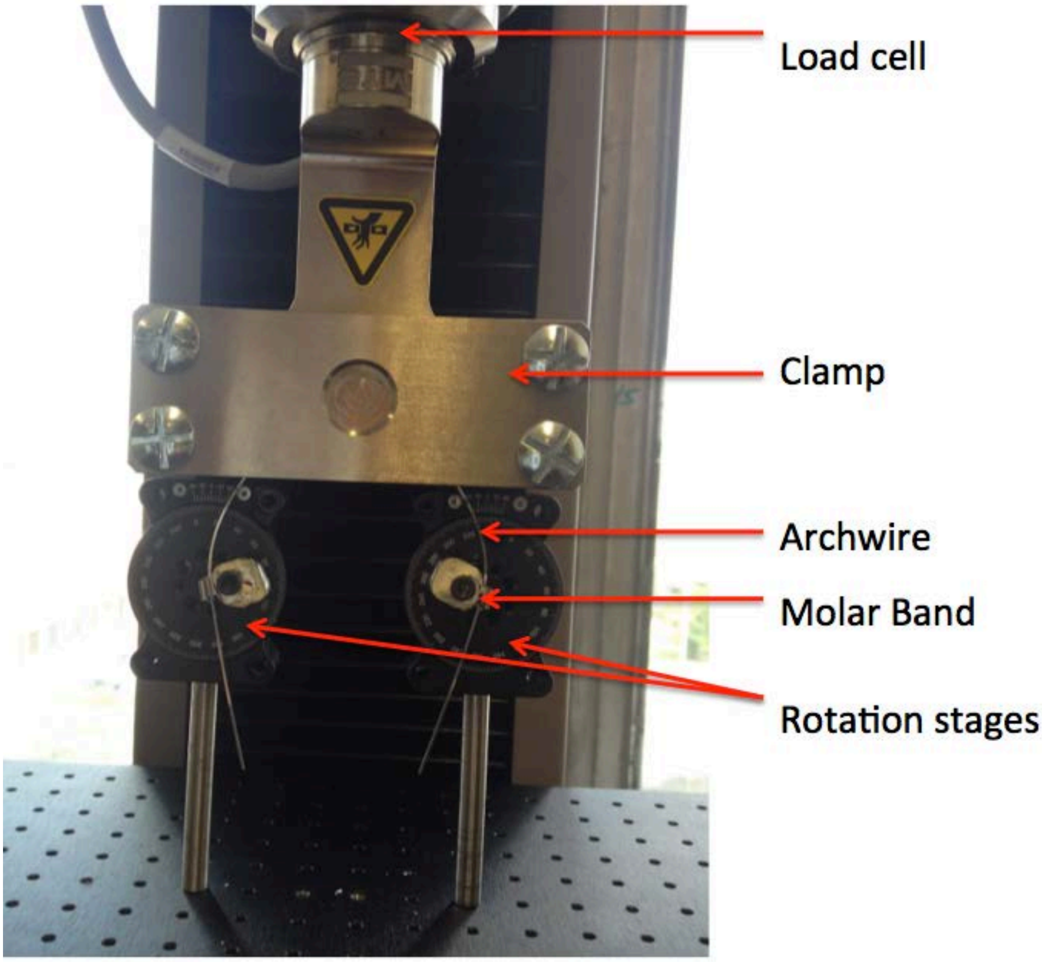

Figure 2.3: Test apparatus – rotational stages

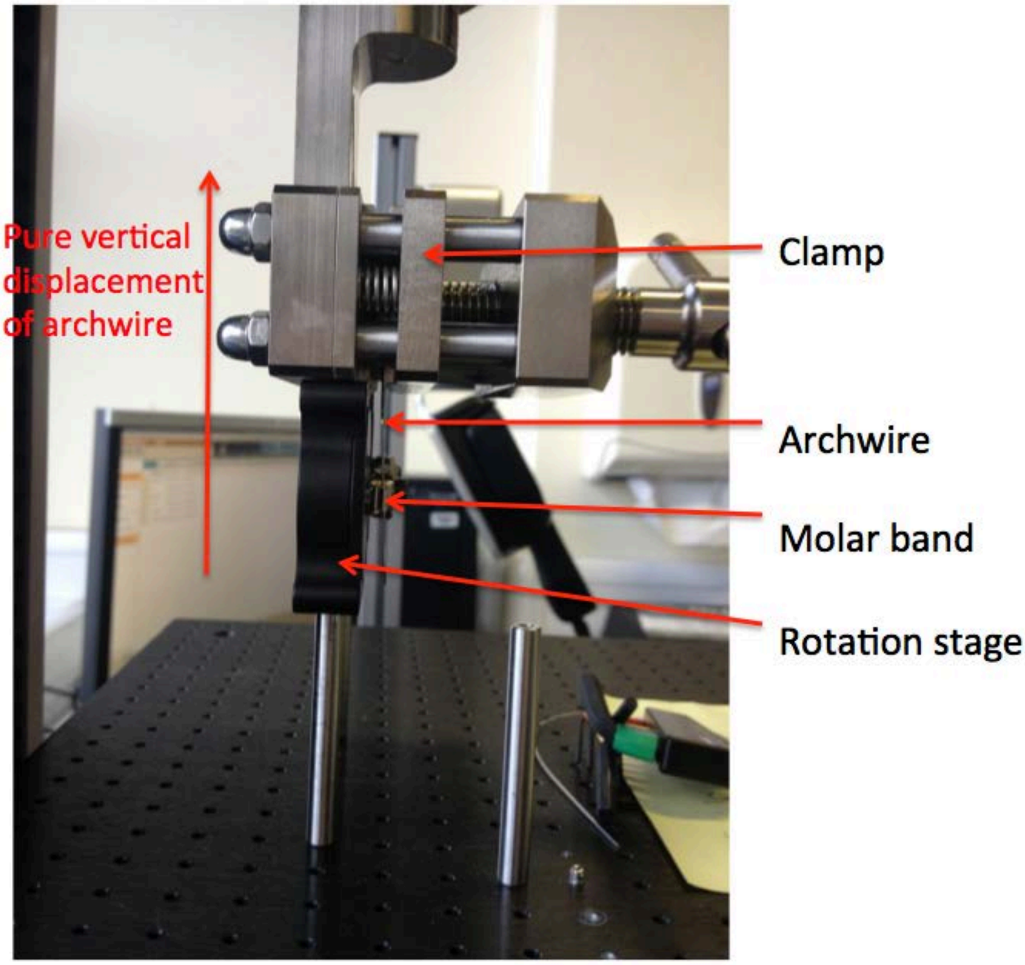

Figure 2.4: Test apparatus – vertical alignment of archwire

The independent variable for this study is the molar rotation and the effect on resistance to sliding. This was tested for three scenarios:

1. Both left and right molars are precisely aligned (both passive)
2. One molar is passive and one molar is palatally rotated (active)
3. Both molars are palatally rotated (active)

There were multiple constant variables that needed to be controlled to allow for the independent variable to be the only factor affecting the dependent variable (resistance to sliding). These control variables were:

- The arch width was controlled by fixing the distance between the molar tubes and the width of the archwire used.
- The length of unsupported archwire was fixed at 18 mm. This was the distance between the upper clamp (replicating the distal surface of the maxillary canine bracket) and the molar tube. The distance was based on the previous study conducted Hamdan and Rock (2008). The distance of unsupported wire reduced the relative stiffness of the archwire so that binding did not completely dominate frictional resistance during testing.
- The angulation and inclination was fixed by incorporating seating grooves on the cast metal head on the rotational stages. This allowed for the bands to be changed and secured in an identical position in all three planes to ensure the tip and torque of the band was not altered between tests.
- The prescription or tube length of the band was not altered between tests. The MBT™ prescription with 10^0 distal offset, 14^0 buccal root torque and 4.6 mm tube length was used for all tests. The tube dimensions were 0.022 x 0.028”. The tube was made from stainless steel. The round EOT was 4.6 mm in length and had a diameter of 1.3 mm
- The crosshead speed was 2 mm/min. Other studies on friction with pre-adjusted edgewise appliances used a crosshead speed of 10 mm/min but this was felt to be too higher rate to fully evaluate the effect of binding (Articolo and Kusy, 1999;Kusy and O'Grady, 2000;Tselepsis *et al.*, 1994).

- The MTS universal test machine was recalibrated to zero prior to each test to account for the weight of the apparatus and drift of the load cell.

Although the value of interest for orthodontists is most commonly static friction, due to the nature of the study it is anticipated that binding will contribute significantly to the overall resistance to sliding. Therefore, the value of kinetic friction will be greater than that of static friction and more relevant to this study. Kinetic friction is represented by the area under the curve of a displacement versus force graph. Raw data from the MTS universal test machine was exported to an excel spreadsheet. The data was analysed using Sigmaplot 12.0 software (Systat software, Inc. Hounslow, London, UK) to calculate the work involved (area under the curve), which equates to the resistance to sliding force.

2.3 Pilot studies

Pilot studies were conducted to evaluate the sensitivity and reproducibility of the test apparatus. The aim of the pilot experiments were:

1. To evaluate the degradation of the archwire and how often it requires replacement
2. To evaluate the degradation of the molar tube and how often it requires replacement
3. To establish if displacement is proportional to work
4. To evaluate if the left and right molar tube experimental results are equivalent and comparable

5. To increase the number of repeat experiments to examine the nature of the relationship between rotation and work, and identify any significant rotations.

The pilot studies were conducted in three groups and provided three datasets accordingly. The groups were:

1. Left buccal rotation – right palatal rotation
2. Left palatal rotation – right buccal rotation
3. Left palatal rotation – right palatal rotation

Based upon previous studies and the results of the ex-vivo data, both left and right molars rotation was varied between 16^0 buccally and palatally rotated. Buccal rotations were examined for completeness and to identify any potential errors in the apparatus prior to the definitive studies. The rotations were altered in 4-degree increments and the experiments conducted randomly to prevent any systematic errors. Data was recorded from 0.1 mm to 10 mm, the minimum displacement detectable by the test apparatus and the maximum displacement that would be expected clinically.

To examine the nature of the relationship between displacement and work, linear regression was used. For each dataset, work was considered as the outcome variable and the displacement the key predictor variable. All individual measurements were included in the analysis. Aside from displacement, the degree of left and right rotation was also included as predictor variables. Initially linear, squared and cubic terms for displacement were included in the analysis. If the cubic term was not found to be statistically significant, this was removed from the analysis and only the linear and squared terms were included.

An additional analysis compared the work values between the first two experimental datasets (left buccal – right palatal, left palatal – right buccal). The datasets were matched up by the rotation values, with the left rotation from the first dataset matched to the right rotation from the second dataset. This was undertaken in order to confirm the set-up of the left and right rotational stages were similar and comparable. Due to the 'paired' nature of the data, the paired t-test was used to compare work values between the two datasets using an alpha value 0.05.

2.4 Definitive studies

Focusing on palatal rotations, the definitive studies divided the experiments into two conceptual groups:

1. The effect of a unilateral molar rotation – right passive and left increasing palatal rotation
2. The effect of a bilateral molar rotation – right palatal and left increasing palatal rotation

When the right molar was passive, its rotation was fixed at zero degrees (i.e. the ideal alignment). When the right molar was active, its rotation was fixed at 10^0. This provided sufficient palatal rotation in order to differentiate from when passive but was not significant enough so that the variable of the left molar rotation could be examined. The left molar rotation was examined between zero and 16^0, altered in two-degree increments.

To validate the accuracy of the results, the left and right molar rotations were switched. The left molar was fixed at a passive alignment of zero degrees or an active alignment of 10^0 palatal rotation. The right molar rotation was examined at 8, 12, 16 and 20-degree rotations. The rotations were extended to 20^0 so that the expected result, calculated from the equation of the relationship found, could be compared with the actual result.

To increase the validity of the results and counteract the increased variation in the results for higher rotations, each experiment was repeated 7 times at the same rotation. Statistical analysis was conducted on the summary data.

The agreement between the repeated measurements was examined by calculating the intra-class correlation (ICC). The pilot studies provided evidence that there was more variation for higher rotations than that of low rotations. To counter this, the analysis was done with the work values on the log scale.

The two datasets were matched by rotation value and the mean work values compared. Due to the 'paired' nature of the data, the paired t-test was used to compare the mean work values. An additional analysis examined how the difference in work between methods was associated with the rotation (that is whether the differences were higher or lower for greater rotations). Due to the continuous nature of both variables, the analysis was performed using Pearson correlation.

2.5 Comparison of straight-wire and extraoral tube

The effect of using the EOT on the molar band opposed to the straight-wire tube was evaluated. The archwire was offset labially immediately below the upper clamp of the MTS machine and passed into the EOT. The experiments were again divided into two groups as per the previous definitive studies. The right molar rotation followed the previous methodology (either fixed at zero or 10^0) and left molar rotation was examined between zero and 12^0, altered in 4-degree increments. Four-degree increments were used because the passive nature of the EOT meant variation in the results for 2-degree increments was minimal and would result in an increased number of tests with little variation in the results.

The paired t-test (matching measurements by rotation) was used to compare the average difference between the straight-wire and EOT group. Pearson correlation was used to examine whether the difference between methods varied by rotation.

Chapter Three

Results

Chapter Three: Results

3.1 Molar rotations

From the sample of 50 study models (100 molars examined), the mean and standard deviation for the angles of Friel and Henry, along with the 95 % normal range are summarized in Table 3.1:

Table 3.1: Mean, SD and 95% normal range for angles of Friel and Henry

Measurement	Mean (Degrees)	Standard deviation	95% normal range
Angle of Friel			
-Left	57.2	5.7	46.0 – 68.5
-Right	57.5	5.2	47.2 – 67.7
Angle of Henry			
-Left	17.1	3.8	9.6 – 24.6
-Right	16.6	3.1	10.5 – 22.8

A sub-sample of measurements from 10 study models (20 % of original sample) was repeated after 120 days and the repeatability was assessed by calculating the intra-class correlation (ICC). The results are summarized in Table 3.2:

Table 3.2: ICC of measurements for angle of Friel and Henry

Measurement	Intra-class correlation (95% CI)
Angle of Friel	
-Left	0.91 (0.71 – 0.98)
-Right	0.97 (0.90 – 0.99)
Angle of Henry	
-Left	0.85 (0.54 – 0.96)
-Right	0.97 (0.89 – 0.99)

The analyses suggested fairly high ICC values for all parameters. The high ICC values suggest good repeatability of the measurements, and validated the results for the two angles measured.

3.2 Pilot studies

The first objective was to evaluate the archwire and molar tube to identify the number of tests the results were comparable, before degradation would affect the results. The archwire was replaced for every test to evaluate the molar tube degradation before the molar tube was replaced for every test to evaluate the archwire. The results found that the archwire was stable for 10 tests before there was a noticeable increase in the variability of the results. The molar tube was found to be stable for over 20 tests. Using these results, it was decided the archwire would be replaced every 5 tests and the molar tube every 15 for the definitive experiments.

A typical displacement-time plot is shown in Figure 3.1. Output data was taken from zero to 300 seconds to reflect the static and kinetic friction involved in the constant displacement of the archwire.

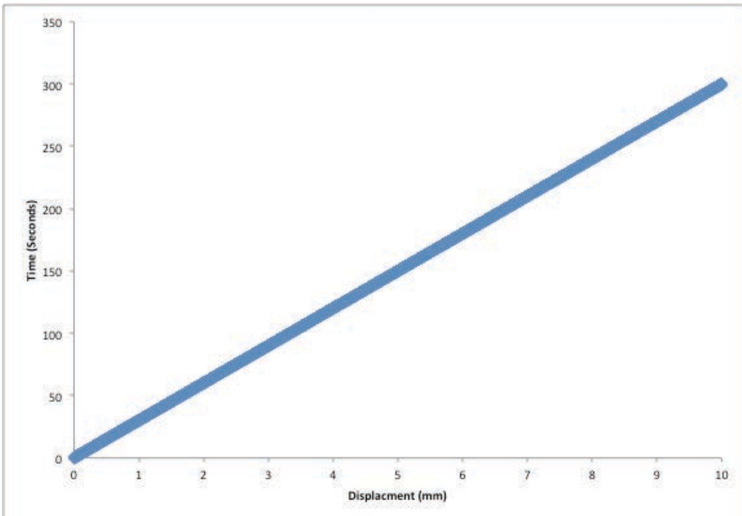

Figure 3.1 – Typical displacement vs. time plot obtained for constant archwire displacement

A summary of the results of higher order terms for displacement (cubic and squared) are shown in table 3.3:

Table 3.3: Summary of pilot study results of higher order terms for displacement

Dataset	Cubic term – P-value	Squared term - P-value(*)
Left buccal – right palatal	0.67	0.45
Left palatal – right buccal	0.77	0.37
Palatal-palatal	0.72	0.86

(*) Obtained after removing cubic term from analysis

The results suggested that for all three datasets, there was no evidence of a significant cubic term. After removing this non-significant cubic term, none of the datasets suggested a significant squared term for displacement. The results conclude that the relationship between displacement and work can be regarded as linear. Graphical illustrations of the fitted linear regression lines demonstrate this linear relationship (Figure 3.1-3.3):

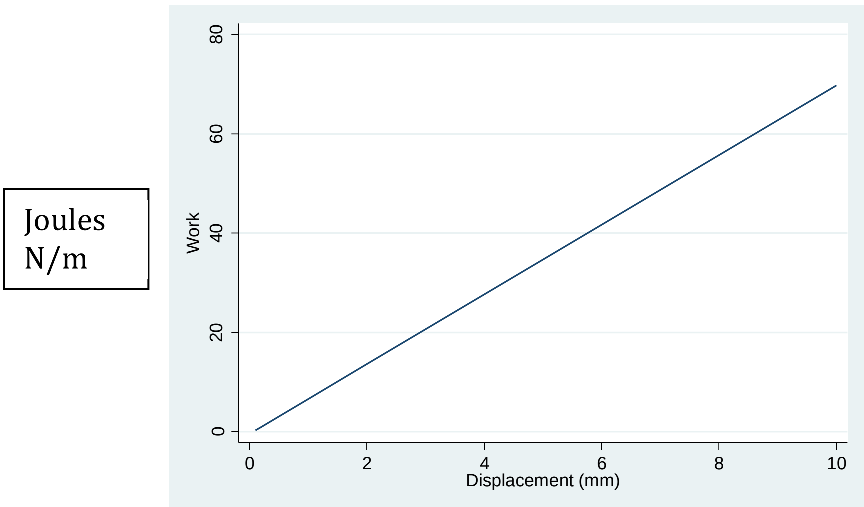

Figure 3.2 – Displacement vs. work for the left buccal rotation – right palatal rotation data ($p<0.001$)

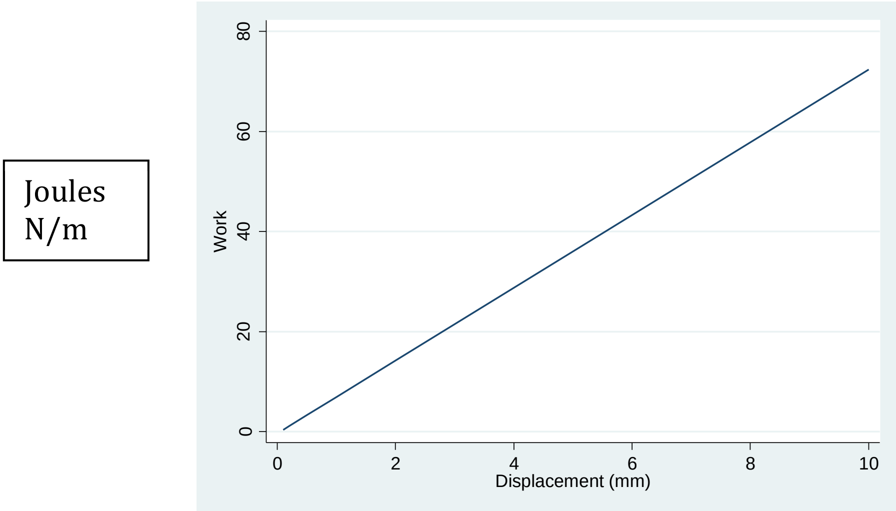

Figure 3.3 - Displacement vs. work for the left palatal rotation – right buccal rotation data (p<0.001)

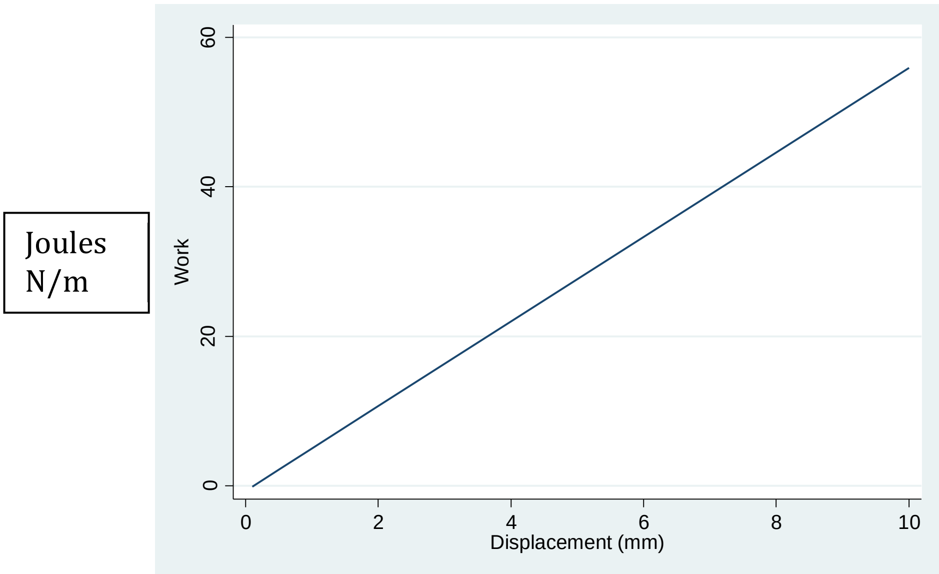

Figure 3.4 – Displacement vs. work for palatal-palatal rotation data (p<0.001)

The first two datasets (left buccal – right palatal and left palatal – right buccal) were matched by the degree of rotation, with the left rotation from the first dataset matched to the right rotation from the second dataset. The work values between the two datasets was compared using the paired t-test (Table 3.4):

Table 3.4: Mean work results and p-value for matched data from left buccal – right palatal and left palatal – right buccal

Displacement (MM)	LB – RP Mean (SD)	LP - RB Mean (SD)	Difference (*) Mean (95% CI)	P-value
10 mm	69 (34)	63 (24)	-6 (-16, 4)	0.24
0.5 mm	2.6 (1.2)	2.4 (0.9)	-0.1 (-0.5, 0.2)	0.45
0.1 mm	0.28 (0.10)	0.22 (0.08)	-0.05 (-0.09, -0.01)	**0.01**

(*) Differences calculated as values for left palatal – right buccal minus left buccal – right palatal

A statistically significant difference was only observed for the 0.1 mm displacement values. The left palatal – right buccal dataset had lower values, with work values 0.05 J (N/m), on average, lower than those for the left buccal – right palatal dataset. The analysis found no significant difference in work for displacement of 10 mm and 0.5 mm.

3.3 Definitive studies

The results for the two data sets examining the effect of a unilateral palatal rotation and bilateral palatal rotation of the molars are shown in appendix 1. The mean and standard deviation of the results are summarised in Table 3.5:

Table 3.5 Mean work values for given displacement according to degree of molar rotation

Right molar (passive/active)	Left molar rotation (degrees)	Mean work for displacement (standard deviation) – Joules (N/m)		
		5mm	0.5mm	0.1mm
Passive	0	2.12 (0.65)	0.45 (0.14)	0.07 (0.03)
	2	2.01 (0.34)	0.41 (0.08)	0.07 (0.01)
	4	2.33 (0.33)	0.45 (0.08)	0.07 (0.02)
	6	3.59 (0.55)	0.72 (0.15)	0.10 (0.03)
	8	4.24 (0.46)	0.85 (0.05)	0.13 (0.02)
	10	5.65 (0.96)	1.26 (0.28)	0.20 (0.05)
	12	6.81 (1.25)	1.42 (0.31)	0.20 (0.04)
	14	8.49 (0.77)	1.93 (0.27)	0.26 (0.07)
	16	12.69 (0.90)	2.50 (0.31)	0.37 (0.05)
Active	0	5.01 (0.61)	0.99 (0.14)	0.14 (0.02)
	2	5.61 (0.67)	1.09 (0.15)	0.16 (0.02)
	4	6.12 (0.49)	1.17 (0.10)	0.17 (0.02)
	6	6.53 (1.46)	1.32 (0.36)	0.20 (0.06)
	8	7.07 (1.75)	1.36 (0.43)	0.20 (0.06)
	10	7.76 (1.39)	1.48 (0.34)	0.20 (0.04)
	12	9.12 (0.44)	1.78 (0.17)	0.26 (0.03)
	14	10.23 (0.67)	2.03 (0.30)	0.28 (0.05)
	16	12.41 (0.84)	2.46 (0.23)	0.33 (0.04)

The ICC to assess repeatability of the measurements at each rotation is shown in table 3.6:

Table 3.6 ICC results for displacements of 5mm, 0.5mm and 0.1mm

Data	Displacement (mm)	ICC (95% CI)
Right passive	5 mm	0.94 (0.86, 0.98)
	0.5 mm	0.92 (0.82, 0.98)
	0.1 mm	0.86 (0.71, 0.96)
Right palatal	5 mm	0.82 (0.64, 0.95)
	0.5 mm	0.74 (0.52, 0.92)
	0.1 mm	0.66 (0.42, 0.89)

The nature of the relationship between rotation and work was analysed using squared and cubic terms for displacement (Table 3.7). The cubic terms were not found to be significant for any displacement values in the right passive data. However, after removal of the cubic terms, the squared terms were significant for all three displacement values. This suggests evidence that there is a non-linear relationship between rotation and work for this dataset. For the right palatal (active) data, the cubic terms were significant for the 5 mm and 0.5 mm data, suggesting evidence of a non-linear relationship. As the cubic terms were significant, the squared terms were not examined further. The cubic terms were not significant for the 0.1 mm data, and the result for the squared term was of borderline statistical significance. This suggests some, although not conclusive, evidence of a non-linear relationship between rotation and work.

Table 3.7 Squared and cubic terms for displacement

Data	Displacement (mm)	Cubic term - P-value	Squared term – P-value (*)
Right passive	5 mm	0.17	**0.001**
	0.5 mm	0.82	**<0.001**
	0.1 mm	0.67	**0.003**
Right palatal	5 mm	**0.003**	-
	0.5 mm	**0.01**	-
	0.1 mm	0.15	0.06

The work values were compared between the right passive and right palatal datasets and a summary of the results is reported in Table 3.8. The figures presented are the mean and standard deviation for each set of data, along with the mean difference between datasets and corresponding confidence intervals. The differences are calculated as value for right palatal minus values for right passive.

Table 3.8 Mean, SD and p-value comparing right passive and right palatal datasets

Displacement (mm)	Right palatal mean work (SD)	Right passive mean work (SD)	Difference (*) mean work (95% CI)	P-value
2 mm	7.8 (2.4)	5.3 (3.6)	2.4 (1.5, 3.4)	**<0.001**
0.5 mm	1.5 (0.5)	1.1 (0.7)	0.4 (0.2, 0.6)	**0.002**
0.1 mm	0.21 (0.06)	0.16 (0.10)	0.05 (0.01, 0.09)	**0.02**

(*)Differences calculated as values for right palatal minus right passive

There was significant difference in the work values between the two datasets, on average, for all displacement values. In each case the work in the right palatal dataset was significantly higher than for the right passive data. The results indicate that there is a significant increase in work to slide the archwire through the molar tube with bilaterally, palatally rotated molars compared with a unilateral, palatal rotation.

The difference between the right passive and right palatal datasets was examined further to see if the differences varied depending on the rotation. Correlation analyses were performed and the results summarised in Table 3.9:

Table 3.9 Correlation analyses to examine if the difference between both groups varied depending on rotation

Displacement (mm)	Correlation Coefficient	P-value
2 mm	-0.83	**0.006**
0.5 mm	-0.88	**0.002**
0.1 mm	-0.79	**0.01**

The results suggested a significant association between the level of rotation and the difference in work between palatal and passive data. All correlations were negative, suggesting that a greater rotation was associated with a less difference between the right passive and right palatal datasets.

Switching the left and right molar tube positions validated the accuracy of the results. The results are presented in Appendix 2. The work involved at a displacement of 0.5 mm and 2 mm was compared between the switched dataset and the previous dataset (un-switched). The results are summarised in Table 3.10. The figures presented are the mean and standard deviation for each set of data, along with the mean difference between datasets and the corresponding confidence interval. The differences are calculated as the results for the un-switched minus the results for the switched.

Table 3.10 Comparison of switched and un-switched mean work measurements to validate accuracy of results and p-value

Data - Displacement (mm)	Unswitched Mean (SD)	Switched Mean (SD)	Difference (*) Mean (95% CI)	P-value
Right fixed – 0.5mm	1.6 (1.0)	1.5 (0.9)	-0.1 (-1.4, 4.1)	0.83
Right fixed – 2mm	7.3 (4.1)	6.8 (3.4)	-0.5 (-6.4, 5.4)	0.76
Right palatal – 0.5mm	1.9 (0.6)	1.8 (0.7)	0.0 (-0.5, 0.4)	0.74
Right palatal – 2mm	9.5 (2.7)	8.6 (2.9)	-0.9 (-2.4, 0.6)	0.12

(*)Differences calculated as values for switched minus unswitched

The results suggested no significant differences in the work values between the switched and unswitched measurements for either dataset, and for both displacements examined.

3.4 Comparison of the straight wire and extraoral tube

The effect of placing the archwire in the EOT opposed to the straight wire tube was examined using the same methodology and dividing the experiments into two groups (right passive and left increasing palatal rotation, right palatal rotation and left increasing palatal rotation). The results are presented in Appendix 3. The paired t-test (matching measurements by rotation) was used to compare the average difference between the two methods (Table 3.11):

Table 3.11 Comparison of the mean difference in work between the EOT versus the straight wire tube

Data – Displacement (mm)	Straight Wire Mean (SD)	EOT Mean (SD)	Difference (*) Mean (95% CI)	P-value
Passive - 2 mm	3.9 (2.4)	0.9 (0.4)	-3.0 (-5.9, 0.0)	0.05
Passive – 0.5 mm	0.79 (0.46)	0.18 (0.07)	-0.61 (-1.24, 0.01)	0.05
Active - 2 mm	6.8 (1.7)	1.3 (0.7)	-5.6 (-7.2, -3.9)	**0.002**
Active – 0.5 mm	1.33 (0.33)	0.29 (0.23)	-1.03 (-1.26, -0.81)	**<0.001**

(*)Differences calculated as values for EOT minus straight wire

The analysis results suggested some evidence of a difference between the two tubes for all analyses. The results for the passive data were only of borderline statistical significance. All analyses found much lower work values for the EOT compared with the straight wire tube.

The Pearson correlation was used to examine whether the difference between methods varied by rotation. The results are summarised in Table 3.12:

Table 3.12 Pearson correlation analyses to compare the EOT with the straight wire tube

Data – Displacement (mm)	Correlation Coefficient	P-value
Passive - 2 mm	-0.94	0.06
Passive – 0.5 mm	-0.93	0.07
Active - 2 mm	-0.99	**0.007**
Active – 0.5 mm	-0.94	0.06

The results found some evidence of an association between difference in work between the two methods and rotation. The results are generally only of borderline statistical significance. The differences between methods were negative (that is lower values for EOT), the negative correlations suggested that the difference between methods was greater for higher rotations.

Chapter Four

Discussion

Chapter Four: Discussion

4.1 Molar rotation

The current evidence base for measuring the degree of the upper first permanent molar rotation suggests the mean angle of Henry to be 11.2 +/- 0.8 degrees (Henry, 1956) and the angle of Friel to be in the range of 57 to 61 degrees (Foresman, 1964;Friel, 1959;Lamons and Holmes, 1961). The use of the angles of Friel and Henry to determine the degree of molar rotation in this study was warranted because the measurements have been shown to be reproducible and have been previously validated (Dahlquist *et al.*, 1996;Friel, 1959;Henry, 1956).

The results for the mean angle of Henry were 17.1 +/- 3.83 degrees for the left molar and 16.6 +/- 3.14 degrees for the right. This suggested that the molars in this sample were, on average, palatally rotated compared with molars that are fully aligned to the optimum angle. This is to be expected as the sample was derived from study models at Birmingham Dental Hospital, where patients would have been assessed as in need of orthodontic treatment. They are therefore unlikely to have an ideal occlusion or well-aligned arches. This finding is in agreement with previous studies evaluating rotation of the first permanent molar rotation in class II malocclusions (Henry, 1956;Lima *et al.*, 2015). The results for the mean angle of Friel did not support this finding. The mean angle of Friel was 57.2^0 for the left molar and 57.5^0 for the right. This was in agreement with the previous studies on the ideal rotational angle for the upper first permanent molar, although on the lower end of the normal range (Foresman, 1964;Friel, 1959;Lamons and Holmes, 1961). It is important to note that errors may have resulted due to an examiner error in identifying the mesio-palatal cusp tip of the molar, anatomical variations of the first permanent molar or, alternatively, this result may be correct with the mean angle of Henry being incorrect.

The repeatability of the measurements was examined by calculating the intra-class correlation (ICC). The analyses suggested fairly high ICC values for all measurements, and particularly high values for the Friel right and Henry right measurements (ICC of 0.97 for both measurements). The high ICC values suggest good repeatability of the measurements.

4.2 Impact of rotated molars on resistance to sliding

The results of this study demonstrated that as the palatal rotation of the maxillary first permanent molar increased, the work involved in sliding the archwire through the molar tube increased, that is there was an increase in the resistance to sliding. For smaller rotations, the displacement-force tracings obtained were comparable with other studies examining friction with fixed appliances (Articolo and Kusy, 1999;Hamdan and Rock, 2008;Moore *et al.*, 2004). Following an initial peak in force as static friction was overcome, the force dropped to a relative plateau. This plateau represents the kinetic friction involved in maintaining movement of the archwire through the molar tube (Figure 4.1).

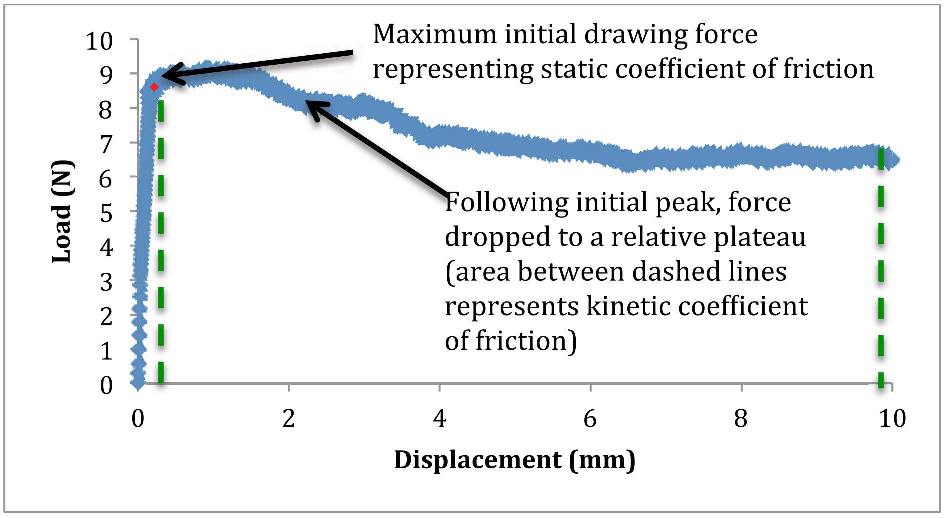

Figure 4.1: Graphical illustration of load vs. displacement for right and left molars in an ideal alignment (zero degrees)

For greater palatal rotations, binding between the molar tube and archwire rapidly became the most significant factor in relation to resistance to sliding. As a consequence, the results obtained differed from those of smaller rotations. Following an initial peak in force as static friction was overcome, the force continued to rise before reaching a relative plateau (Figure 4.2). Occasionally, with more significant palatal rotations the force continued to rise the further the archwire was displaced. Moore *et al* (2004) and Hamdan and Rock (2008) found similar variation in frictional tracings when examining the effect of tip on friction. Moore *et al* (2004) concluded that small increases in tip resulted in rapidly increasing frictional forces, with frictional resistance doubling with every degree of tip. They felt this occurred as a result of increased binding between the archwire and bracket. The effect of increasing tip can be expected to be similar to increasing rotation, and their results are comparable to the exponential trend found with increasing palatal rotations.

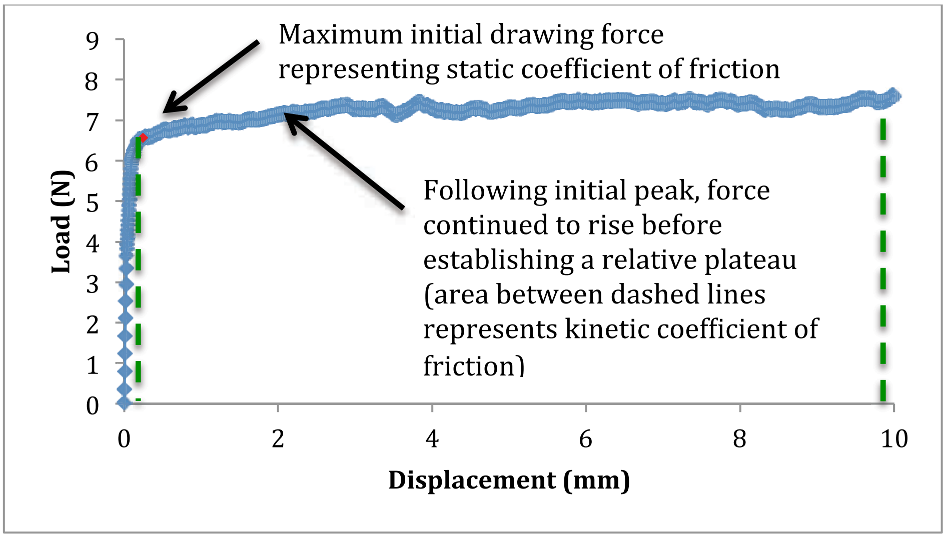

Figure 4.2: Graphical illustration of load vs. displacement for right and left both 12 degrees palatally rotated

The relationship between work and displacement was found to be linear for all rotation couples, as it was not significantly significant for cubic or squared terms. The relationship between extent of molar rotation and work was significant for cubic and squared terms, providing evidence of a non-linear relationship. An exponential increase in work with increasing palatal rotation provided the best fit to the results of the study. This can be explained because binding increases significantly as the molar rotation increases. The stiffness of the stainless steel archwire and lack of alignment of the wire and tube, coupled with the binding occurring, results in the need for rapidly increasing force levels in order to maintain the movement of the archwire through the molar tube.

Previous studies on orthodontic friction have displaced a bracket along an archwire. This study differed as a molar tube was used opposed to a bracket. The width of the tube is longer and the archwire is enclosed within the tube without a need for separate ligation. Therefore, even after a small rotation of the molar tube, binding can rapidly occur and dominates friction in relation to resistance to sliding. This creates an inability to accurately identify static and kinetic friction values. Resistance to sliding swiftly enters the second phase as defined by Burrow (2009), where resistance to sliding is equal to the binding that occurs between the molar tube and bracket.

Articolo and Kusy (1999) investigated the influence of the angulation between the archwire and bracket on the resistance to sliding (N), and designed a mathematical model for understanding the relative impact of binding and friction to resistance to sliding. The results demonstrated a linear relationship for all resistance to sliding (N) regression lines. As the angulation between the bracket and archwire was increased, the force required to maintain movement increased. Comparison of the regression lines demonstrated that resistance to sliding increased with increasing angulation between the archwire and bracket, as the regression line was noticeably higher. Interestingly the distance between the lines was fairly constant and the lines were approximately parallel. They suggested the parallelism of the lines indicated that friction does not change with increased angulation but was caused by the increased binding between the archwire and bracket. The results indicated that binding approximately accounted for 80 % of the resistance to sliding for all couples when the contact critical angle was 7^0. It showed that binding began to dominate frictional resistance shortly after the archwire bracket changed to an active configuration. With further increases in angulation, binding continued to be greatly more significant than frictional resistance (Articolo and Kusy, 1999). The effect of rotation is expected to be almost identical to that of angulation, if not more significant. The implications in relation to the results obtained from this study indicate that the increased resistance to sliding resulted from the increased binding that occurred and not as a result of increased frictional resistance.

The clinical implications of these results provide significant evidence for derotation of the upper first permanent molars prior to fitting of a transpalatal or Nance palatal arch. If a transpalatal arch is used, the molars could be derotated using the appliance prior to the commencement of overjet reduction. Should the molars be significantly rotated, the forces required to slide the archwire through the molar tube are substantial and may prevent tooth movement as the applied orthodontic force would not be sufficient in order to overcome binding. Should the applied force be increased, it significantly increases the risk of orthodontic induced root resorption, pain, discomfort and even anchorage loss.

4.3 Impact of unilateral palatal rotation

The impact of a unilateral palatal rotation was assessed with the right molar tube fixed at a passive rotation (i.e. ideal alignment) and the left molar tube with increasing palatal rotation. The results suggest that a unilateral, increasing palatal rotation resulted in an exponential increase in work for all amounts of displacement. Graphical illustration of the relationship between degree of rotation and work for an archwire displacement of 0.5 mm and 2 mm is shown in Figure 4.3:

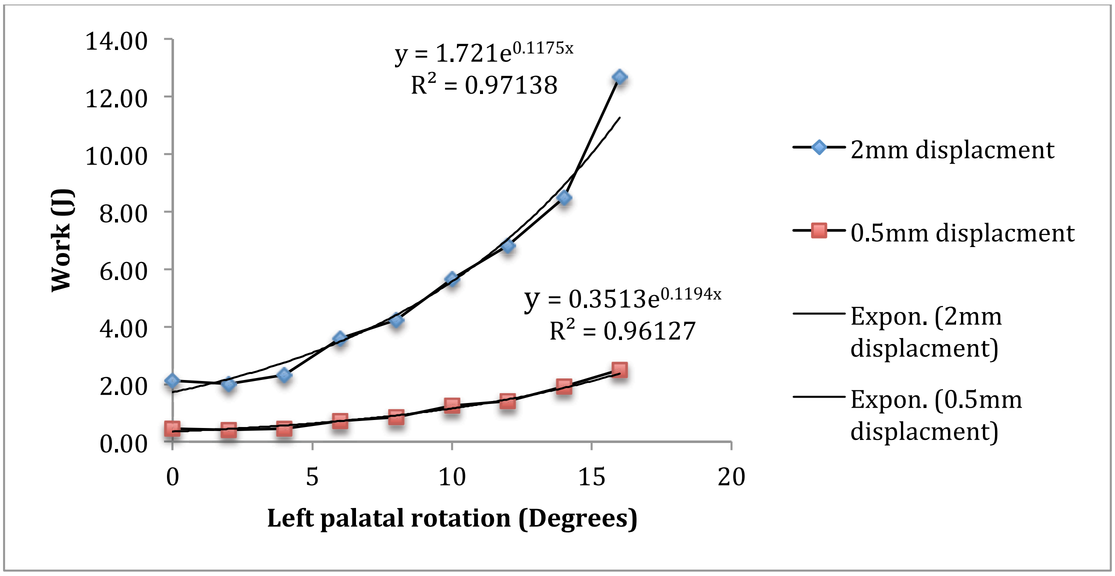

Figure 4.3: Graphical illustration of the relationship between degree of rotation and work for an archwire displacement of 0.5mm and 2mm for a unilateral palatal rotation (right passive – left increasing palatal rotation)

Examination of the relationship between molar rotation and work were not found to be significant for any of the displacement values. After removal of the cubic terms, the squared terms were significant for archwire displacement of 0.1 mm, 0.5 mm and 2 mm. This suggests evidence that there is a non-linear relationship between molar rotation and work involved to move the archwire through the straight wire tube.

An exponential relationship between the degree of molar rotation and work provided the best fit for the results of the experiments. An R^2 value of 0.96 for 0.5 mm displacement and 0.97 for 2 mm displacement suggests it is an accurate representation of the relationship. The ICC analyses suggested good repeatability of the experimental measurements with values approaching, or exceeding 0.9.

4.4 Impact of bilateral palatal rotations

The impact of bilateral palatal rotations was assessed with the right molar tube fixed at an active palatal rotation of 10^0 and the left molar tube with increasing palatal rotation. The work involved in sliding the archwire through the molar tube, on average, was significantly greater than for a unilateral palatal rotation (p-value of 0.002 and 0.02 for displacement of the archwire by 0.5 and 0.1 mm respectively). The results were in agreement with the impact of a unilateral palatal relationship and suggested an exponential relationship existed between increasing palatal rotation and work. Graphical illustration of the relationship between degree of rotation and work for an archwire displacement of 0.5 mm and 2 mm is shown in Figure 4.4:

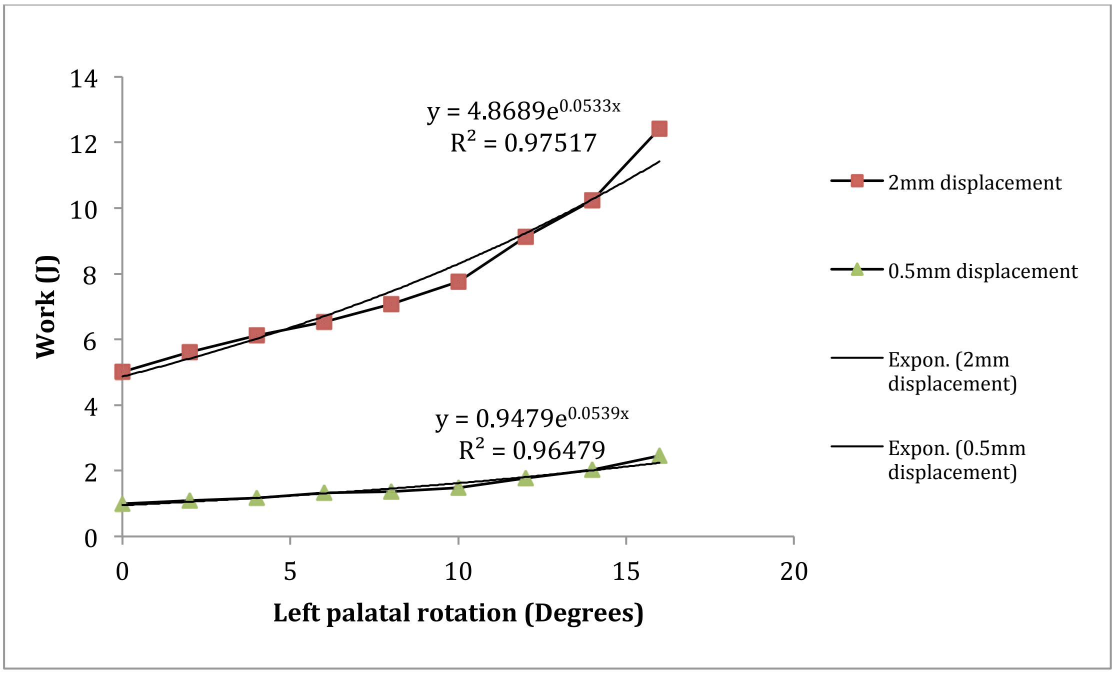

Figure 4.4: Graphical illustration of the relationship between degree of rotation and work for an archwire displacement of 0.5mm and 2mm for bilateral palatal rotations (right fixed palatal rotation – left increasing palatal rotation)

Examination of the relationship between molar rotation and work was conducted for this dataset. The cubic terms were significant for the 5 mm and 0.5 mm data, suggesting evidence of a non-linear relationship. As cubic terms were significant, squared terms were not examined. The cubic term was not significant for the 0.1 mm data, and the result for the squared term was of borderline statistical significance. This suggests some, although not conclusive, evidence of a non-linear relationship between degree of molar rotation and work. The work measurements obtained for 0.1 mm displacement were small and the results can be explained by the small sample size or the results obtained being marginally outside the sensitivity of the MTS machine.

An exponential relationship between the degree of molar rotation and work provided the best fit for the results of the experiments. An R^2 value of 0.96 for 0.5

mm displacement and 0.98 for 2 mm displacement suggests it is an accurate representation of the relationship. The ICC analyses suggested agreement was poorer between the measurements than the results obtained when the right molar tube was passive. The ICC values were much lower, with a value of 0.74 for the 0.5 mm displacement and 0.66 for the 0.1 mm displacement. This can be explained as having both molars palatally rotated is expected to significantly increase the binding between the archwire and the bracket. The occurrence of the binding varies greatly, resulting in an increased variability and slight unpredictability of the work values obtained by the experimental apparatus.

4.5 Comparison of unilateral and bilateral palatal rotations

Comparing the data between a unilateral and bilateral palatal rotation, the analysis results suggested that there was a significant difference in the work values between the two datasets, on average, for all displacement values. In each variation the work values in the bilateral palatal rotation group was significantly higher than for the unilateral group.

Whilst there was an average difference between the two groups, the difference between the groups was examined further to see if the differences varied depending on the rotation. Pearson correlation analysis suggested a significant association between the level of rotation and the difference in work (p-value of 0.002 and 0.01 for displacement of the archwire of 0.5 and 0.1 mm respectively). All correlations were negative, suggesting that a higher rotation was associated with a less difference between the two groups. This convergence of the work involved for higher rotations with a unilateral or bilateral molar rotation is illustrated in Figure 4.5. This implies that as the palatal rotations reach a certain degree, whether unilateral or bilateral, the work involved in sliding the archwire through the molar tube begins to plateau. As binding is the main factor responsible for the increase in work, the results suggest there is a maximum threshold of binding above which increasing the molar rotation does not increase the work required to displace the archwire. Once this level is reached, although the work involved is substantial, unless notching occurs the work involved will begin to plateau.

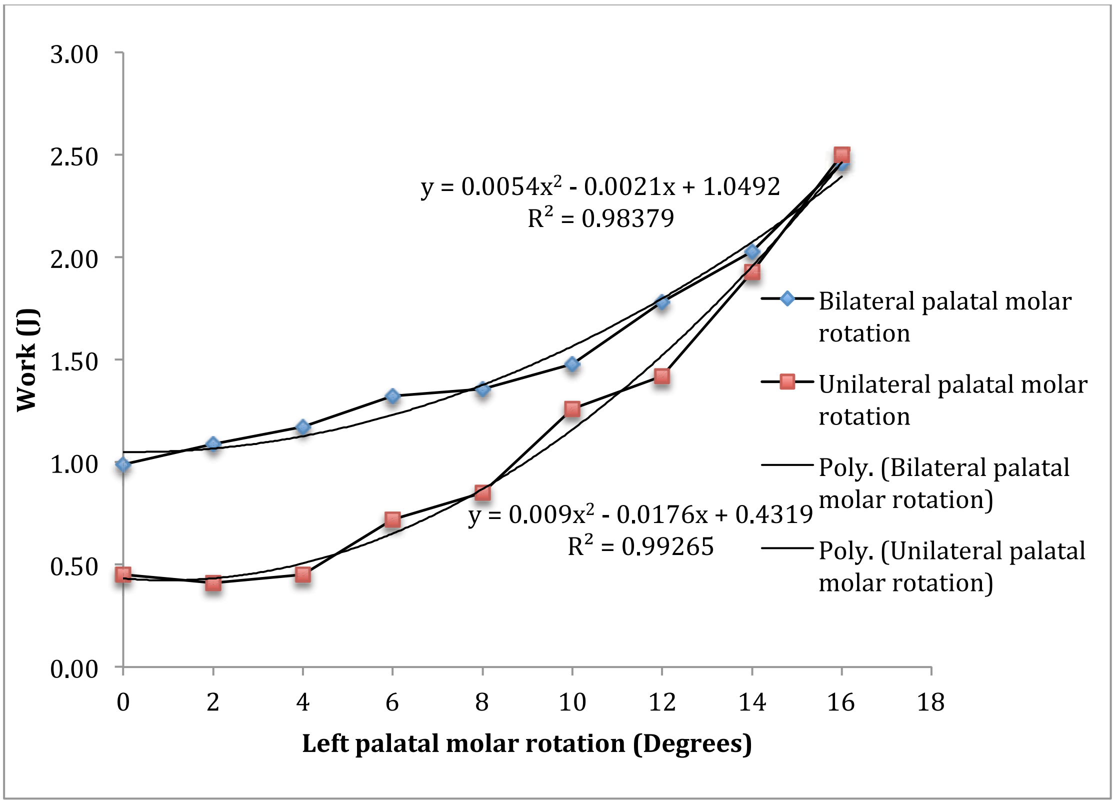

Figure 4.5: Graphical illustration of the convergence of work involved for higher rotations with a unilateral or bilateral molar rotation

4.6 Validation of the results

By switching the left and right molar tube rotations, it was aimed to validate the results by comparing the two results. Should they be comparable it would suggest the results obtained were an accurate representation of the dynamic resistance to sliding that was occurring. The pilot studies previously conducted had suggested that the left and right molar tubes were correctly set-up and their rotations comparable.

The paired t-test was used to compare the work between the switched and un-switched groups. The results suggested no significant differences in the work values between the groups for either 0.5 mm or 2 mm archwire displacement. For both unilateral and bilateral palatal rotations the p-value was greater than 0.05. However, these analyses were based on only 3 measurements, these being the rotations that were common to both methods.

4.7 Comparison of the straight wire and extraoral tube

Inserting an offset into the archwire and passing it through the EOT significantly reduced the work involved in displacing the archwire compared with using the straight wire tube. Graphical illustrations comparing the work involved in displacing the archwire by 2 mm and 0.5 mm between the EOT and straight wire tube are shown in Figures 4.6-4.9:

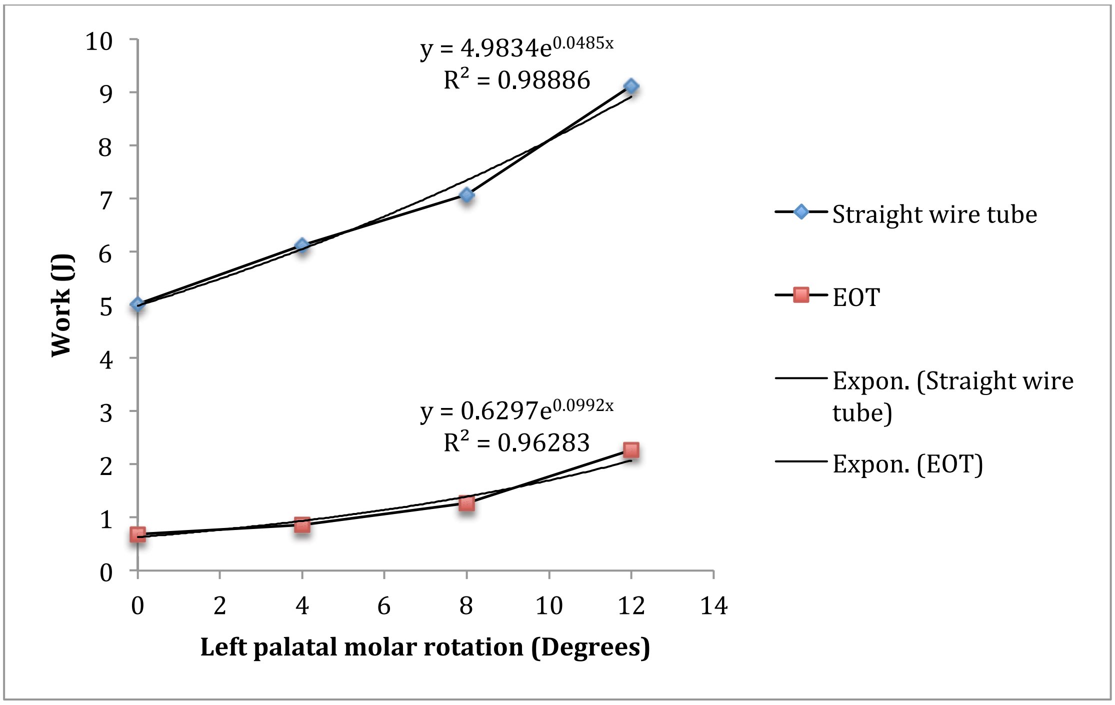

Figure 4.6 – Comparison of work involved in displacing the archwire 2mm between the EOT and straight wire tube for bilateral palatal rotations (right fixed palatal – left increasing palatal rotation)

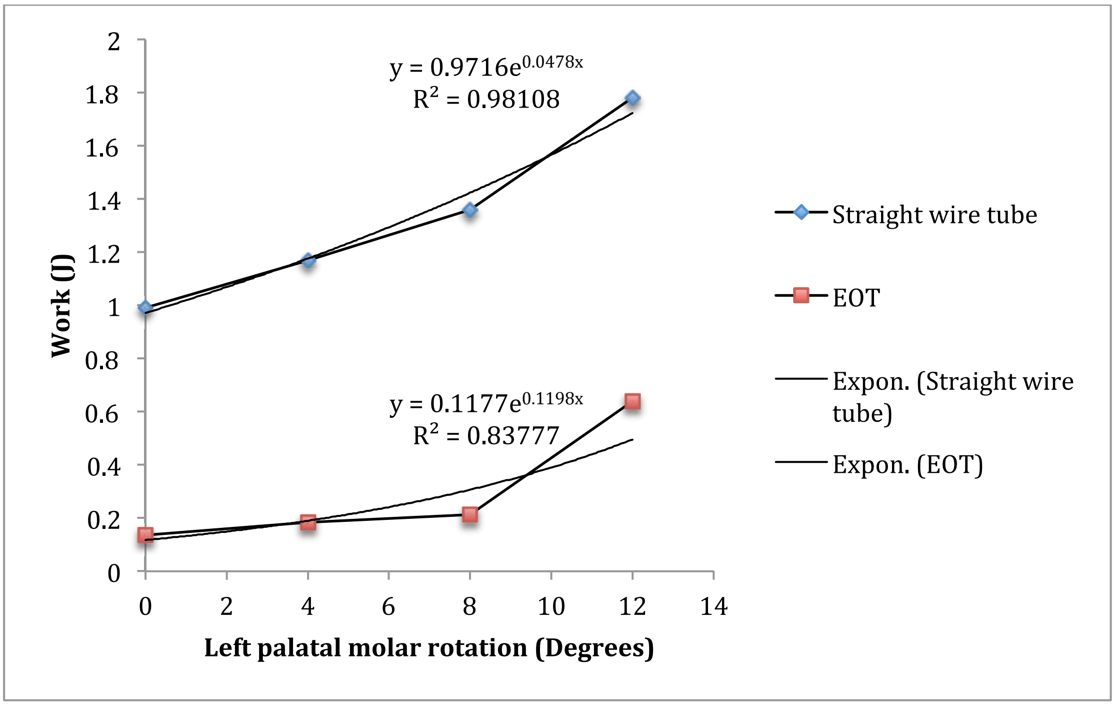

Figure 4.7 – Comparison of work involved in displacing the archwire 0.5mm between the EOT and straight wire tube for bilateral palatal rotations (right fixed palatal – left increasing palatal rotation)

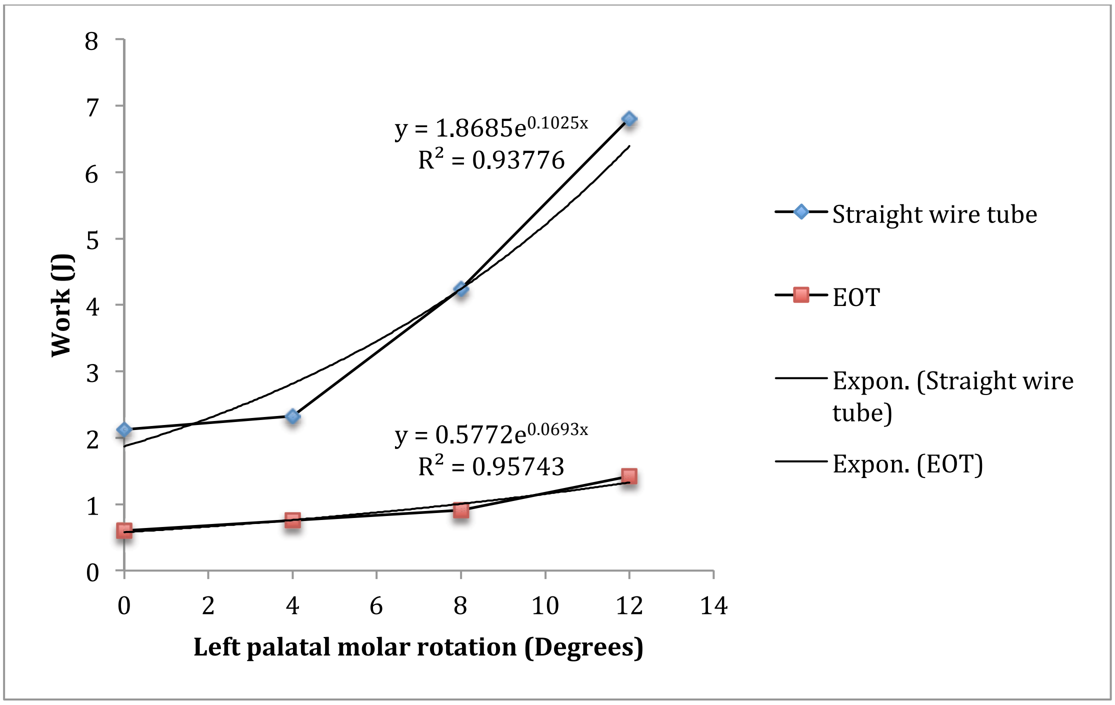

Figure 4.8 – Comparison of work involved in displacing the archwire 2mm between the EOT and straight wire tube for unilateral palatal rotations (right passive – left increasing palatal rotation)

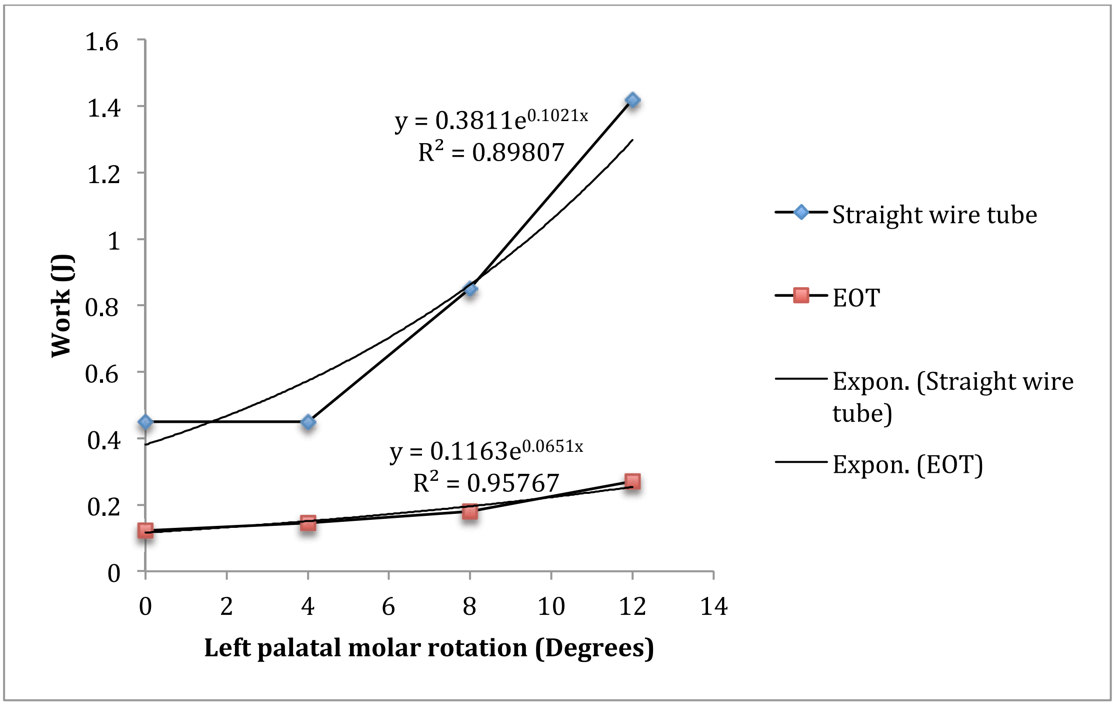

Figure 4.9 – Comparison of work involved in displacing the archwire 0.5mm between the EOT and straight wire tube for unilateral palatal rotations (right passive – left increasing palatal rotation)

Matching the measurements by rotation, the paired t-test was used to compare the average difference between the EOT and straight wire tube. The results suggested some evidence of a difference between the two tubes for all analyses. The results for a bilateral palatal rotation found a significant reduction in work for the EOT compared with the straight wire tube for all displacements. The p-value was 0.002 and <0.001 for 2 mm and 0.5 mm respectively. The results for the unilateral palatal rotation, with the right molar fixed at zero degrees, were only of borderline statistical significance (p-value of 0.05). However, there were larger differences in work values, and the lack of significance is likely to be mainly attributed to the small number of data points. All analyses confirmed much lower work values for the EOT compared to the straight wire tube.

The difference between the EOT and straight wire tube was examined to identify if the differences varied depending on the rotation. Pearson correlation analyses suggested some evidence of an association between difference in work between the two tubes and the rotation. The results are generally only of borderline statistical significance. However, the correlations are very large and the lack of statistical significance is mainly attributed to the small sample size. Given that the differences between the two tubes were negative (lower work values for EOT), the negative correlations suggested that the difference between methods was greater for higher rotations.

4.8 Limitations of interpreting results

Whilst the results of this study provide some strong evidence regarding the effect on resistance to sliding that the use of a palatal arch with rotated molars has, there are certain aspects that limit the interpretation of the results.

The methodology of the study was comparable with previous studies but there were some key differences. Due to the nature of the experimental apparatus, it did not fully replicate a full mouth typodont. Use of full arch typodont, with brackets ligated to the archwire may have given a clearer picture of the dynamic interaction occurring between the bracket and archwire with regards to the resistance to sliding. This lab-based study can never replicate the environment of oral cavity and does not account for other significant factors that affect friction and resistance to sliding. Main examples include occlusal and masticatory forces.

The main difference in the methodology of this study compared with previous literature was that resistance to sliding was examined opposed to static or kinetic friction. As binding rapidly became the most significant factor affecting the resistance to sliding of the archwire, evaluation of the friction involved would have been inappropriate. It would have been impossible to separate the binding and friction components of the overall resistance to sliding and make any conclusions from the results. The large variability of the nature of binding that occurred affected the results because it significantly affected the reproducibility of the results of higher rotations.

The experimental apparatus was designed to allow each experiment to be set-up and conducted under almost identical conditions. No brackets were incorporated mesial to the molar tube to allow the full effect of the varying molar rotations to be evaluated. This resulted in a longer span of unsupported archwire then might be encountered clinically, thus increasing the flexibility of the rectangular, stainless steel archwire. The implications of using this design mean the results obtained underestimated the effect of palatal rotations due to the ability of the archwire to flex in a palatal direction. This would not occur clinically, therefore conclusions on the relationship found between molar rotations and resistance to sliding can be accepted but the work involved in displacing the archwire may vary clinically.

The sample size with regards to certain statistical analysis was small. A larger sample would have given greater power to the statistical analysis in order to provide more conclusive evidence. The study focused on multiple key areas regarding molar rotations, resistance to sliding and the use of the EOT. To allow for better interpretation of the results, the study could be divided into smaller studies and repeated with a greater number of repeat experiments and molar rotations.

4.9 Other factors that affect friction

As previously discussed, the aetiology of friction is multi-factorial and the results obtained from a clinical study would vary from the results of this lab-based study. Multiple variables were standardised so that the effect of molar rotation with a trans-palatal arch was evaluated. Biological factors, mainly saliva and occlusal forces, have a significant effect on friction that is very difficult to replicate in the laboratory. Research into the role of saliva has provided varying and often conflicting results, with evidence to suggest a lubricating or adhesive influence. Baker *et al* (1987) reported that artificial saliva reduced frictional resistance with stainless steel archwires by 15-19 %. This was in contrast to a study by Downing *et al* (1995) who concluded that artificial saliva increased friction compared to when tested in a dry state.

The effect of occlusal forces has been examined clinically and in lab-based studies. A clinical trial with patients asked to chew softened gum to evaluate the effect of masticatory function on friction found no significant reduction (Iwasaki *et al.*, 2003). Braun *et al* (1999) applied perturbations to the orthodontic appliance and found that frictional resistance was almost completely eliminated every time the appliance was tapped. They concluded that masticatory function did reduce friction but its effect was unpredictable and inconsistent. It is important to remember that occlusal forces can also prevent tooth movement completely by the interlocking nature of a patient's occlusion.

Variation in the fixed appliances and their set-up has a significant and highly variable effect on friction. The bracket material, prescription, width and inter-bracket distance have a significant effect, that varies between patients. These factors will alter the frictional resistance within the appliance.

4.10 Future research

The study has provided evidence to support the need for a clinical trial to evaluate the effectiveness of the use of the EOT compared with the straight wire tube with a Nance palatal arch, regardless of the molar rotation. The resistance to sliding is significantly reduced when using the EOT and this method of anchorage reinforcement may prove to be of clinical benefit.

To develop the concept further of using the EOT tube, a further lab-based study should be conducted with a larger sample size (number of experiments). This would give the research more statistical power and the ability to provide more conclusive evidence. This includes the potential for inclusion of a reduced number of molar rotations as a variable, to give a more accurate reflection of what would be encountered clinically.

The design of the experimental apparatus can be adapted for further research into friction and resistance to sliding. It would be possible to investigate the effect of different arch widths and their effect on resistance to sliding. The width of the archwire can be adapted to investigate the effect of expanded or contracted archwires. Furthermore, placing torque in the archwire in the posterior segment and its effect on resistance to sliding would provide some valuable clinical information regarding the mechanics of orthodontic treatment.

The tube dimensions on the molar band were standardised in this study but this is a variable that could be investigated, as a range of molar tube dimensions are currently available. No high quality literature is currently available on the effect of molar tube length on friction or resistance to sliding.

Notching of the archwire was not investigated as part of this study but some valuable scientific knowledge could be gained by examining the archwires with a scanning electron microscope. Following testing of various molar rotations, the archwire could be examine to evaluate the effect rotated molars have on notching.

Chapter Five

Conclusion

Chapter Five: Conclusions

The use of a transpalatal or Nance palatal arch with rotated molars results in an exponential increase in work in order to slide an archwire through a molar tube.

- The relationship between work and displacement was found to be linear for all rotation couples.
- The relationship between work and molar rotation was found to be non-linear, with an exponential increase in work with increasing palatal rotations.
- Bilaterally, palatally rotated molars resulted in a significantly increased amount of work for all amounts of displacement of the archwire compared with a unilateral rotation.
- Pearson correlation analysis found a significant association between extent of molar rotation and difference in work between unilateral and bilateral rotated molars.
- Use of the extraoral tube significantly reduced the work required to displace the archwire through the tube compared with the straight wire tube. For a unilateral palatal rotation this was of borderline statistical significance but for bilateral palatal rotated molars this was highly significant.

Clinicians need to evaluate molar alignment prior to fitting of a transpalatal or Nance palatal arch. For noticeable rotations, consideration should be given to derotation prior or use of the extraoral tube in order to reduce the resistance to sliding in order to reduce the reactionary forces on the anchor teeth.

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Appendices

Appendix 1

Table of results for unilateral palatally rotated molar (right is passive at zero degrees and left is increasing palatal rotation)

Rotation (degrees)	Test number	Mean and standard deviation (SD)	Work for given displacement (Joules)		
			2mm	0.5mm	0.1mm
R0L0	1		2.24	0.42	0.06
	2		3.26	0.71	0.11
	3		1.94	0.38	0.06
	4		1.65	0.34	0.05
	5		2.59	0.58	0.1
	6		1.33	0.3	0.04
	7		1.8	0.43	0.07
		Mean	2.12	0.45	0.07
		SD	0.65	0.14	0.03
R0L2	1		2.06	0.42	0.07
	2		1.66	0.32	0.05
	3		2.06	0.45	0.07
	4		1.52	0.32	0.05
	5		2.55	0.53	0.09
	6		2.22	0.46	0.07
	7		1.97	0.38	0.06
		Mean	2.01	0.41	0.07
		SD	0.34	0.08	0.01
R0L4	1		2.44	0.52	0.08
	2		2.37	0.49	0.08
	3		2.1	0.38	0.05
	4		1.84	0.33	0.05
	5		2.81	0.57	0.09
	6		2.15	0.4	0.06
	7		2.59	0.47	0.07
		Mean	2.33	0.45	0.07
		SD	0.33	0.08	0.02
R0L6	1		2.91	0.55	0.08
	2		3.96	0.93	0.15
	3		3.3	0.67	0.1
	4		4.6	0.91	0.13
	5		3.46	0.59	0.07
	6		3.26	0.75	0.11

	7		3.65	0.64	0.08
		Mean	3.59	0.72	0.10
		SD	0.55	0.15	0.03
R0L8	1		4.49	0.94	0.14
	2		4.68	0.84	0.11
	3		4.86	0.82	0.1
	4		3.64	0.8	0.12
	5		4.19	0.87	0.14
	6		3.93	0.84	0.13
	7		3.86	0.84	0.14
		Mean	4.24	0.85	0.13
		SD	0.46	0.05	0.02
R0L10	1		4.56	0.98	0.16
	2		4.55	0.97	0.15
	3		6.19	1.68	0.27
	4		6.92	1.55	0.25
	5		5.06	1.08	0.17
	6		5.69	1.19	0.18
	7		6.6	1.36	0.21
		Mean	5.65	1.26	0.20
		SD	0.96	0.28	0.05
	1		5.68	1.27	0.19
R0L12	2		5.01	0.91	0.13
	3		7.53	1.58	0.22
	4		8.51	1.8	0.27
	5		6.13	1.2	0.17
	6		7.8	1.64	0.23
	7		7.01	1.52	0.21
		Mean	6.81	1.42	0.20
		SD	1.25	0.31	0.04
R0L14	1		8.66	1.86	0.26
	2		8.23	1.78	0.29
	3		7.56	1.47	0.2
	4		9.13	1.93	0.28
	5		9.65	2.29	0.12
	6		8.63	2.2	0.35
	7		7.6	2	0.29
		Mean	8.49	1.93	0.26
		SD	0.77	0.27	0.07
	1		10.86	2.11	0.31

R0L16	2		12.37	2.11	0.32
	3		13.43	2.8	0.37
	4		13.16	2.68	0.4
	5		12.51	2.56	0.37
	6		13.38	2.87	0.4
	7		13.11	2.36	0.44
		Mean	12.69	2.50	0.37
		SD	0.90	0.31	0.05

Table of results for bilateral palatally rotated molars (right is fixed at a palatal rotation of 10 degrees and left is increasing palatal rotation)

Rotation (degrees)	Test number		Work for given displacement (Joules)		
			2mm	0.5mm	0.1mm
R10L0	1		4.54	0.88	0.12
	2		5.73	1.16	0.17
	3		4.96	1	0.14
	4		5.99	1.21	0.17
	5		4.51	0.86	0.11
	6		4.82	0.93	0.13
	7		4.54	0.87	0.13
		Mean	5.01	0.99	0.14
		STD	0.61	0.14	0.02
R10L2	1		5.86	1.11	0.17
	2		6.85	1.39	0.19
	4		5.64	1.12	0.16
	5		5.47	1.03	0.14
	6		5.63	1.07	0.16
	7		5.18	1.03	0.16
	8		4.66	0.88	0.14
		Mean	5.61	1.09	0.16
		STD	0.67	0.15	0.02
R10L4	1		6.06	1.11	0.15
	2		5.51	1.06	0.17
	3		6.93	1.32	0.17
	4		6.02	1.12	0.15
	5		6.43	1.25	0.19
	6		6.3	1.26	0.19
	7		5.58	1.09	0.16
		Mean	6.12	1.17	0.17

		STD	0.49	0.10	0.02
R10L6	1		7.88	1.63	0.25
	2		9.13	1.95	0.3
	3		5.64	1.11	0.16
	4		5.39	1.04	0.16
	5		5.25	0.97	0.13
	6		5.83	1.19	0.2
	7		6.61	1.38	0.22
		Mean	6.53	1.32	0.20
		STD	1.46	0.36	0.06
R10L8	1		7.63	1.5	0.23
	2		10.56	2.25	0.33
	3		6.56	1.17	0.16
	4		7.31	1.33	0.19
	5		6.48	1.24	0.18
	6		5.59	1.02	0.15
	7		5.35	1	0.16
		Mean	7.07	1.36	0.20
		STD	1.75	0.43	0.06
R10L10	1		8.17	1.59	0.22
	2		10.43	2.09	0.27
	3		7.19	1.14	0.14
	4		6.25	1.16	0.16
	5		6.61	1.25	0.19
	6		8.22	1.63	0.18
	7		7.48	1.49	0.23
		Mean	7.76	1.48	0.20
		STD	1.39	0.34	0.04
R10L12	1		9.38	1.74	0.26
	2		9.41	1.98	0.29
	3		8.73	1.52	0.2
	4		8.34	1.59	0.26
	5		9.35	1.9	0.28
	6		9.55	1.9	0.28
	7		9.07	1.84	0.23
		Mean	9.12	1.78	0.26
		STD	0.44	0.17	0.03
R10L14	1		9.61	1.71	0.28
	2		9.88	1.95	0.24
	3		9.3	1.77	0.22

	4		11.19	2.54	0.36
	5		10.65	1.97	0.26
	6		10.31	1.95	0.24
	7		10.66	2.31	0.33
		Mean	10.23	2.03	0.28
		STD	0.67	0.30	0.05
R10L16	1		11.27	2.42	0.35
	2		12.35	2.24	0.28
	3		12.48	2.21	0.27
	4		12.78	2.62	0.39
	5		11.51	2.28	0.3
	6		13.8	2.72	0.35
	7		12.71	2.73	0.34
		Mean	12.41	2.46	0.33
		STD	0.84	0.23	0.04

Appendix 2

Table of results for switching left and right molar tube position – Left passive and right increasing palatal rotation

Rotation (degrees)	Test number	Work for given displacement (Joules)	
		2mm	0.5mm
R8L0	1	3.53	0.75
	2	2.28	0.48
	3	2.85	0.64
	4	3.16	0.52
	5	3.38	0.56
	6	3.35	0.6
	7	2.47	0.47
	Mean	3.00	0.57
	SD	0.48	0.10
R12L0	1	7.76	1.72
	2	7.4	1.58
	3	8.37	1.8
	4	8.1	1.76
	5	8.4	1.85
	6	6.48	1.41
	7	8.28	1.77
	Mean	7.83	1.70
	SD	0.70	0.15
R16L0	1	8.36	2.09
	2	5.18	1.25
	3	9.93	2.18
	4	10.47	2.49
	5	10.76	2.55
	6	11.87	2.87
	7	10.64	2.54
	Mean	9.60	2.28
	SD	2.22	0.52
R20L0	1	17.34	3.84
	2	17.6	3.87
	3	11.23	2.52
	4	9.28	2.06
	5	17.51	3.92

	6	17.42	3.91
	7	17.51	3.91
	Mean	15.41	3.43
	SD	3.57	0.79

Table of results for switching left and right molar tube position – Left fixed palatal and right increasing palatal rotation

Rotation (degrees)	Test number	Work for given displacement Joules	
		2mm	0.5mm
R8L10	1	7.47	1.51
	2	5.07	0.9
	3	5.11	1.03
	4	6.28	1.37
	5	5.32	1.08
	6	4.91	0.98
	7	4.84	0.98
	Mean	5.57	1.12
	STD	0.97	0.23
R12L10	1	7.83	1.46
	2	8.51	1.9
	3	7.99	1.77
	4	9.4	2.11
	5	10.03	2.26
	6	8.69	1.94
	7	9.38	2.1
	Mean	8.83	1.93
	STD	0.81	0.26
R16L10	1	11.92	2.47
	2	12.49	2.61
	3	11.27	2.35
	4	12.21	2.6
	5	10.44	2.26
	6	10.48	2.25
	7	11.09	2.42
	Mean	11.41	2.42
	STD	0.82	0.15
R20L10	1	16.05	3.33
	2	13.37	2.82

	5	13.13	2.85
	6	14.49	3.12
	7	13.22	2.86
	9	14.98	3.25
	10	14.47	3.17
	Mean	14.24	3.06
	STD	1.08	0.21

Appendix 3

Table of results for extraoral tube

Rotation (degrees)	Test number	Work for given displacement (Joules)		
		2mm	0.5mm	0.1mm
R0L0	1	0.671	0.335	0.148
	2	0.392	0.19	0.09
	3	0.612	0.276	0.119
	4	0.699	0.313	0.136
	5	0.631	0.28	0.119
	Mean	0.601	0.279	0.122
	SD	0.122	0.055	0.022
R0L4	1	0.846	0.412	0.187
	2	0.757	0.344	0.15
	3	0.687	0.261	0.11
	4	0.68	0.296	0.127
	5	0.801	0.349	0.153
	Mean	0.754	0.332	0.145
	SD	0.072	0.057	0.029
R0L8	1	0.81	0.316	0.135
	2	0.852	0.384	0.173
	3	0.984	0.455	0.21
	4	0.904	0.332	0.148
	5	0.991	0.516	0.236
	Mean	0.908	0.401	0.180
	SD	0.080	0.084	0.042
R0L12	1	1.394	0.553	0.289
	2	1.448	0.677	0.304
	3	1.517	0.637	0.332
	4	1.458	0.568	0.211
	5	1.302	0.492	0.22
	Mean	1.424	0.585	0.271
	SD	0.081	0.073	0.053
R10L0	1	0.698	0.323	0.149
	2	0.733	0.227	0.099
	3	0.672	0.292	0.129
	4	0.62	0.278	0.13

	5	0.704	0.364	0.173
	Mean	0.685	0.297	0.136
	SD	0.043	0.051	0.027
R10L4	1	0.737	0.328	0.153
	2	0.733	0.322	0.176
	3	0.944	0.422	0.195
	4	0.95	0.424	0.197
	5	0.956	0.426	0.198
	Mean	0.864	0.384	0.184
	SD	0.118	0.054	0.019
R10L8	1	1.259	0.456	0.21
	2	1.244	0.45	0.21
	3	1.25	0.452	0.211
	4	1.289	0.466	0.217
	5	1.298	0.467	0.215
	Mean	1.268	0.458	0.213
	SD	0.024	0.008	0.003
R10L12	1	2.39	1.135	0.555
	2	2.592	1.403	0.668
	3	2.245	1.376	0.637
	4	2.041	1.432	0.669
	5	2.052	1.439	0.673
	Mean	2.264	1.357	0.640
	SD	0.234	0.127	0.050