Initial forces experienced by the anterior and posterior teeth during dental-anchored or skeletal-anchored en-masse retraction in an in vitro dental arch

by

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Abstract

Objectives: To evaluate the initial forces generated by retraction springs during en-masse retraction space closure on a simulated maxillary dental arch. To compare these initial retraction forces on the anterior and posterior teeth between traditional dental-anchorage and skeletal anchorage.

Methods: A simulated dental arch (OSIM) measured forces and moments in 3-dimensions acting on each tooth generated by retraction springs used for en-masse retraction space closure. Three treatment groups were compared that represented 1) traditional dental-anchorage, 2) skeletal anchorage, 3) skeletal anchorage with power arms.

Results: Dental anchorage produced the largest protraction forces on the posterior teeth of 1.77 ± 0.10N. Skeletal anchorage reduced protraction forces to 0.05 ± 0.08N and 0.01 ± 0.02N, without and with power arms respectively. The anterior teeth segment experienced the least vertical forces in the dental-anchored group 0.01 ± 0.07N. Skeletal anchorage increased vertical forces to 0.98 ± 0.70N. The addition of power arms created 0.57 ± 0.11N of vertical force, between the dental-anchored and the skeletal-anchored without power arms groups. Retraction forces on the anterior teeth segment were similar between the dental-anchored and skeletal-anchored groups at 2.99 ± 0.27N and 3.05 ± 0.14N. The addition of power arms to skeletal-anchorage increased retraction forces to 3.30 ± 0.30N.

Conclusions: Skeletal anchorage significantly reduced protraction forces on the posterior teeth but significantly increased vertical forces on the anterior teeth. The addition of power arms during skeletal-anchorage reduced the increase in vertical forces on the anterior teeth but was still greater than dental-anchored vertical forces.

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List of Symbols and Abbreviations used

ANOVA – Analysis of variance

C_{res} – Center of resistance

C_{rot} – Center of rotation

CI – Confidence interval

Fx, Fy, Fz – Force along the x-, y-, z- axis

M_C – Moment o the couple

M_F – Moment of the force

M_X, M_Y, M_Z – Moment around the x-, y-, z- axis

OSIM – Orthodontic simulator

SPSS – Statistical product and service solution

Teeth numberering system – FDI system. (quadrant.tooth, ex. 1.3)

1 Chapter 1: Introduction and Literature Review

1.1 Statement of the problem

Although orthodontic treatment may yield many benefits for a patient including improved occlusal function, oral health, and esthetics, treatment can also potentially pose risks to the patient by harming the oral tissues. Poor control of tooth movement during treatment can directly lead to tissue damage or may cause harm indirectly by increasing overall treatment time. Movement of teeth into poorly supported tissues can result in periodontal attachment loss and bone dehiscence. Long treatment duration increases the time for plaque accumulation and caries destruction, and external root resorption is correlated with treatment time.[1] Therefore, better control of tooth movement during orthodontic treatment will reduce the burden of treatment and improve outcomes for the patient.

Currently, a major difficulty in orthodontics is accurately predicting the resultant tooth movement from an applied force. Traditionally the strategy to study forces and tooth movements required the simplification of the force system to a *determinate force system*. Within this type of force system, the acting forces and moments can be accurately measured and evaluated. This allowed the study of one-tooth and two-tooth systems, as well as one-couple/two-couple systems. Unfortunately, it is common practice in clinical orthodontic treatment to involve multiple teeth in the dental arch by ligating them onto a single continuous archwire which increases the complexity of the system to that of an *indeterminate force system*, where accurate tooth movement prediction is difficult. Within an indeterminate force system, only approximations of force levels can be calculated and only the direction of moments can be determined. This increases the complexity in the system and can result in unforeseen side-effects during treatment.

Although experience has taught orthodontists to develop techniques to mitigate treatment side-effects, the need to correct them inevitably increases overall treatment length.

Closure of extraction spaces involves a complex force system where forces act on teeth on either side of the extraction site. During the space closure, these teeth will move in all three dimensions. In some cases, these movements are unwanted, such as unwanted extrusion or intrusion of teeth. Currently there is limited understanding of the forces exerted on teeth during closure of extraction spaces, both adjacent to and further away from the extraction site. By studying the forces in three-dimensions that act on teeth during space closure, a better correlation can be made between applied forces and tooth movements, which could improve treatment outcomes.

1.2 Introduction

Tooth movement in orthodontics involves mechanical forces acting on a biological system. Forces are generated from the various orthodontic bracket and wire configurations as well as auxiliary orthodontic appliances. The biological system being acted upon includes the tooth and its supporting periodontium, most notably the periodontal ligament and the alveolar bone. Although the study of how forces affect tooth movement has been studied for many decades, the present understanding is still limited.

1.2.1 Biomechanical Principles

Forces acting on teeth can initiate tipping, rotation, or translation, which can alter the position of the tooth in the dental arch. Forces are represented by three-dimensional vectors containing both a direction and a magnitude. The unit of force typically quoted in orthodontic literature is *grams* (gm) force, but the international system of unit (S.I. unit) for force is *Newtons*

(N). The position of the force vector is determined by its point of application on the tooth. Two or more forces can be combined by adding their vectors where the vector sum represents the resultant force vector. In this way, multiple forces acting on the same object can be simplified by mathematically combining them into a single resultant vector. Thus the net tooth movement from multiple forces can be predicted by the resultant force vector.

The moment of a force (M_F) results from a force that does not pass through the center of resistance of an object. When a force is applied some non-zero distance away from the center of resistance, an object will tend to rotate around its center of rotation. The magnitude of the moment of the force is equal to the multiplication of the force magnitude by the perpendicular distance from the center of resistance to the line of action of the force. This distance is often referred to as the *moment arm*. Then the component of the force that is perpendicular to moment arm is calculated. The moment of the force is then the product of the distance times the perpendicular component force. Similar to forces, moments of the force have both a direction and an amplitude. The direction of a moment is perpendicular to the two-dimensional plane created by the force vector and the moment arm and can be determined by the *right-hand* rule. Moments can cause rotation in one of two ways around the moment vector that are defined as positive and negative with respect to the axis of rotation. The same rules of summation can be applied to moment vectors such that a resultant vector can be represented as the sum of all the component vectors. If the sum of all the moment vectors is zero, then the net moment of the force will also be zero and no rotation will occur.[2]

The center of resistance (C_{res}) of a tooth is the point where if a force is directed through it, the tooth will undergo translation without any rotation. The specific location of the center of resistance varies from tooth to tooth and varies based on root length, height of alveolar bone, crown-root ratio, and root morphology. In general, the center of resistance is inaccessible to direct force application because it resides within the alveolar bone. On average, the center of resistance of a maxillary central incisor is approximately 8-10mm away from a typical orthodontic bracket slot.[3] Due to the inaccessibility of the center of resistance of teeth, orthodontic forces act away from the center of resistance and will produce a moment of the force. This results in tipping of teeth, which is the most common tooth movement in orthodontics.

The center of rotation (C_{rot}) is the point around which a tooth will rotate when a moment acts on the tooth. Whereas the center of resistance typically resides somewhere within the tooth mass, the center of rotation can exist anywhere from within the tooth mass to a point an infinite distance away. When the position of the center of rotation and center of resistance coincide, a tooth will undergo pure tipping, also known as uncontrolled tipping. In this scenario the tooth crown and its roots will move in opposite directions. When the position of the center of rotation is at infinite distance from the center of resistance, the tooth will undergo pure translation, also known as bodily movement. This scenario occurs when a force is applied through the center of resistance and results in the tooth crown and its roots moving in the same direction by an equal amount. When the center of rotation is some position intermediate between infinite and at the center of resistance, the tooth will undergo some combination of rotation plus translation.

A couple is produced when two parallel non-collinear forces of equal magnitude but opposite direction act on the same tooth. This will generate a moment that will tend to rotate the tooth. The moment of the couple can be calculated by multiplying the magnitude of one of the forces and the perpendicular distance between the two force vectors (lines of action of both forces). A property of couples is that the moment generated does not depend on where the force is applied, only the distance between the two forces. Thus, as long as the distance between the forces is constant, a couple can be applied anywhere on the tooth and will result in the same moment of the couple.

The moment-to-force ratio is an important concept exploited in modern edgewise orthodontics. Tooth movement is primarily influenced by two components: applied forces which create moments of the force (M_F), and couples which create moments of the couple (M_C) (Fig 1.1).

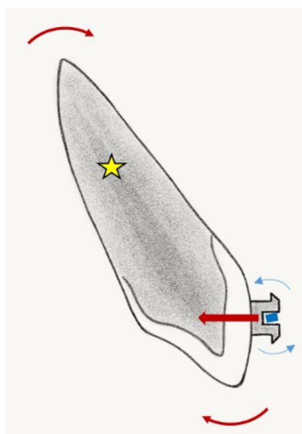

Figure 1.1. Moment of the force and moment of the couple. The force exerted by the archwire on the tooth represented by the straight red arrow, which creates the moment of the force (red curved arrows). The rectangular archwire generates a couple in the orthodontic bracket that creates the moment of the couple (blue curved arrows). Center of resistance represented by star.

Dimensional archwires are capable of generating couples when acting on brackets and as such can create a moment of the couple. The ratio between M_C and M_F, known as the moment-to-force ratio dictates what type of tooth movement will result.[4]

By carefully managing M_C and M_F, tooth movement can be altered to preferentially express specific wanted movements and minimize unwanted movements (Fig 1.2).

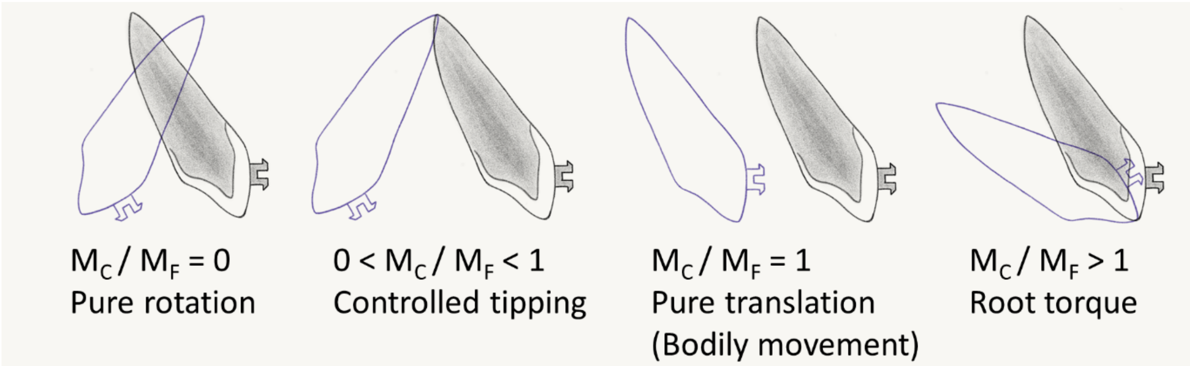

Figure 1.2. Moment to force ratios and their effect on tooth movements.

1.3 Study Significance

The study of appliance mechanics promises to benefit orthodontics by improving our understanding of how to control tooth movements and increase its predictability. Currently there are deficits in our understanding of how forces affect tooth movements in complex force systems. One such force system is during en-masse retraction space closure following extraction of first premolars, where the anterior six teeth are retracted reciprocally against the posterior six teeth. Clinically, unwanted side-effects have been reported during space closure including intrusion or extrusion of the anterior or posterior teeth. Additionally, tipping of teeth rather than the more desirable bodily movement of teeth during space closure can occur. Although attempts have been made to mitigate these unwanted side-effects, including skeletal anchorage and power arms, they still persist indicating that a gap in knowledge still exists. To improve our knowledge, it is important to study orthodontic loads acting in all three dimensions to help understand both the wanted as well as the unwanted movements. Furthermore, studying the entire dental arch simultaneously is important since multiple teeth are involved during en-masse retraction space closure. While current literature has explored the biomechanics of one- or two-teeth systems, or numerically studied the forces in the dental arch using finite element analysis, no study has measured the three-dimensional forces of the entire dental arch during en-masse retraction space closure. Thus, this study will provide the force measurements expressed on teeth at the onset of en-masse retraction and further our knowledge of the biomechanics of space closure.

1.4 Research aim

1) To compare the vertical and horizontal forces experienced by the six anterior teeth as a segment between dental anchorage, skeletal anchorage, and skeletal anchorage with power arms.
2) To compare the component of force along the three axes (x-, y-, z- axis) experienced by the posterior anchor teeth between dental anchorage, skeletal anchorage, and skeletal anchorage with power arms.
3) To compare the vertical (z-axis) force profiles along the dental arch between dental anchorage, skeletal anchorage, and skeletal anchorage with power arms.

1.5 Hypotheses

1) H_O: There is no difference in vertical forces on the anterior teeth segment between the skeletal anchorage groups and dental anchorage group
2) H_O: There is no difference in retraction forces on the anterior teeth segment between the skeletal anchorage groups and dental anchorage group
3) H_O: There is no difference in protraction forces on the posterior teeth segment between the skeletal anchorage groups and dental anchorage group
4) H_O: There is no difference in inward palatal forces on the posterior teeth segment between the skeletal anchorage groups and dental anchorage group

5) H_O: There is no difference in vertical forces on the posterior teeth segment between the skeletal anchorage groups and dental anchorage group

1.6 Literature review

1.6.1 Optimizing applied forces for tooth movement

There has been great interest for orthodontists to understand the relationship between applied forces and tooth movement to better manage treatment outcomes. One area that has drawn attention is determining the optimal forces to achieve the maximal rate of tooth movement. Early experiments on animal models were used to generate force curves and their correlation with tooth movement. Experiments have shown that tooth movement occurs within a range of forces that are bounded by a minimal force necessary to initiate the physiologic processes necessary for bone remodeling and a maximal force where cell death and hyalinization occur leading to a lag phase before tooth movement can commence. The lower bound of forces has been shown to be very light with 5 grams (0.05N) capable of initiating tooth movement.[5] The upper bound is less defined but the heavy forces that typically result in the lag phase occur around and above 300g (3N). Within this range of 5g-300g (0.05N–3N), the rate of tooth movement varies. Some studies believe there to be a linear relationship between rate of tooth movement and magnitude of force within that range. This hypothesis was proposed to be due to the type of tooth movement that occurs at different force levels. At low forces more dental tipping may occur, while at higher forces more bodily movement may occur and the transition from tipping to bodily movement occurs in a linear fashion.[6] However, other studies suggest that the rate of tooth movement does not follow a linear progression and instead is constant. Following a lag phase due to hyalinization, maximal tooth movement during space closure was observed in the range of 5 – 11 ounces (150g-300g or 1.5N-3N).[7] Another study corroborated the findings of constant rate of tooth movement reporting no difference between 50g (0.5N), 100g (1N), or 200g (2N) of retraction force and found the rate of tooth movement to be 2.5mm per month.[8]

One explanation for the discrepancy in the findings on rate of tooth movement is that different animal models were used. While animal models offer better control of experimental variables, human studies are the main end goal as they offer the greatest application of findings to everyday clinical situations. Studies of retraction within human subjects have typically used either elastomerics or Nickel-Titanium (NiTi) retraction springs. While elastomeric materials tend to break down with time and thus force delivery decays over time, NiTi retraction springs have the ability to provide a constant force profile over a certain span of activation distances.[9] This constant force profile of NiTi retraction springs appears to benefit the rate of tooth movement as studies have found a significant increase in tooth movement when compared with elastomeric modules[10] or elastic ligatures.[11] However, the force decay experienced by elastomerics may have the benefit of acting as an automatic safety shut off, such that if a patient is lost to follow-up, there is less worry about unwanted additional tooth movement. To overcome the force decay, elastomerics are frequently exchanged with new modules either by the patient or the clinician. This necessitates patient compliance either through directly exchanging the elastomeric modules or attending scheduled appointments to have them exchanged by the clinician. Any lapse in patient compliance would reduce the optimal rate of tooth movement and help explain the difference in tooth movement achieved by NiTi retraction springs. Force measurements have found that the force in the range of 150g-250g (1.5N-2.5N) to retract canines with NiTi retraction springs produced the most rapid tooth movement. Elastic modules, which produce approximately 180g (1.8N) of force fall within the 150g-250g (1.5N-2.5N) range as well. Lighter forces in the range of 100g (1N) was found to produce a slower rate of tooth movement.[10,11] These findings support the hypothesis that the rate of tooth movement varies linearly with force up to a point after which point the tooth movement does not change.[12]

1.6.2 Management of anchorage during tooth movement.

In orthodontics it is often desirable to move some teeth more than others. One such case is during space closure where it is preferable to close the space by moving one of the teeth adjacent to the space more than the other. However, force systems in orthodontics act reciprocally, which places equivalent forces on the teeth on either side of the extraction space. This reciprocal space closure would tend towards moving both teeth equally. Over the years, different techniques have been developed to overcome this reciprocal space closure in order to preferentially move desired teeth. Cortical anchorage and stationary anchorage were used by Tweed to increase the forces required to move one set of teeth compared to the other and conceptually allow the same reciprocal force to have different effects on the opposing teeth.[5]

Another technique used to manage anchorage was proposed in 1950 by Begg, which used the idea that differential forces could be used to manage tooth movement. In the 1950's, Smith and Storey's animal experiments found that when heavy forces in the range of 400-600g (4N-6N) were used during retraction, more movement of the posterior teeth resulted. Increased posterior tooth movement as compared to anterior tooth movement is known as *anchorage loss* and is useful in certain circumstances to the clinician. Conversely, lighter forces in the range of 150g-250g (1.5N-2.5N) tended to retract the anterior teeth (canines) more than the posterior teeth.[5] Therefore, the concept of differential forces could be used to preferentially move the anterior teeth or the posterior teeth. The working hypothesis for why differential forces created different tooth movements was derived from the force curves used to study forces and tooth movements (Fig 1.3). Force curves showed that above some minimal threshold required to initiate tooth movement, there was a linear relationship between forces and rate of tooth movement until a plateau was reached, where increasing the force did not change the rate of tooth movement. Above this plateau range, increased forces tended to decrease tooth movement, a phenomenon hypothesized to be due to cellular death and hyalinization requiring undermining resorption. In general, the biological system is overwhelmed above a certain force and needs to first repair damage before it can initiate tooth movement.[12] With the understanding of the force curves, careful manipulation of forces could manage the rates of tooth movement of anterior and posterior segments.

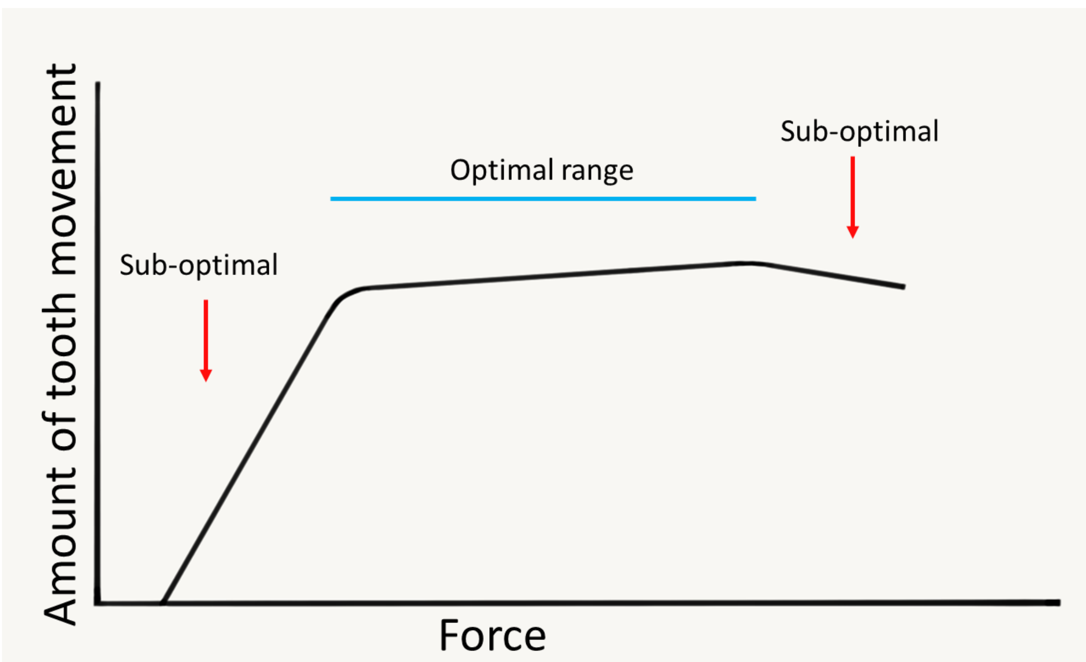

Figure 1.3. Force curve for tooth movement.

The influence of the size and number of teeth on anchorage has long been exploited by orthodontists. Larger teeth and additional teeth increase the force required to move them and thus reduces the amount of movement that results from an equivalent force. The influence of the larger teeth or additional teeth is more accurately represented by the amount of root surface area resisting applied forces.[5,12] The effect of root surface area on anchorage is illustrated during space closure when different teeth are extracted. When first premolars are extracted, the resultant space closes with 66.5% used by the incisor retraction, while the remaining 33.5% is closed by the posterior protraction. However, when the second premolars are extracted, the ratio becomes about 56.3% anterior and 43.7% posterior movement. In the first premolar extraction scenario, the anterior incisor unit was composed of six teeth, but when second premolars are extracted, this unit is composed of eight teeth. Thus in cases where greater posterior anchorage is desired, extraction of first premolars is indicated over extraction of second premolars.[13] The use of root surface area to manage anchorage is known as *reinforced anchorage*. Knowledge of force curves can be used in tandem with reinforced anchorage to preferentially move desired teeth. If a force is used that nearly maximizes the tooth movement of the anterior teeth while being sub-maximal with the posterior teeth, then theoretically more anterior tooth movement should occur.[12] The extreme situation of this technique would be where there is little to no movement of the posterior teeth and primarily movement of the anterior teeth during retraction. This theoretical situation is termed *maximum anchorage*, also known as *A anchorage*. The opposite scenario where space closure is primarily the result of posterior tooth protraction is termed *C anchorage*. Investigation into *A anchorage* and *C anchorage* scenarios has yielded mixed results. Some studies report C anchorage occurring at high force values but other studies have found that both segments always move and that increasing forces simply moves the anterior and posterior segments faster.[5,14] Therefore the exact relationship between forces and anchorage remains elusive at this time.

1.6.3 Skeletal anchorage

Traditional reinforcement of anchorage would involve extra-oral devices such as headgear. However, headgear demands patient compliance for the treatment to be effective and poor compliance can result in unreliable anchorage.[15] Additionally, headgear has been associated with injury to soft tissues and eyes.[16] An alternative method of reinforcing anchorage is skeletal anchorage via bone screws. The first reported case of bone screw use in orthodontic treatment came in 1983 when Creekmore and Eklund placed bone screws in the anterior nasal spine to achieve maxillary incisor intrusion.[17] Since then, bone screws have routinely been used as temporary anchorage devices (TAD) and have reported to be well tolerated with low morbidities.[18,19] Typical treatment scenarios for the use of TADs are during intrusion of teeth, distalization of molars, or space closure.[20-22] By removing the burden of anchorage from the posterior teeth, there appears to be evidence that skeletal anchorage is more effective than conventional anchorage at reinforcing anchorage. However, there does not seem to be any difference in treatment time between the two types of anchorage.[23]

1.6.4 Center of resistance of the anterior teeth segment

As teeth are retracted during space closure, care is taken by the orthodontist to avoid excessive tipping of the teeth. Uncontrolled tipping results in the dental crowns moving faster than their roots. This can lead to divergent roots away from the space closure site when the crowns are in contact. At this stage the clinician must spend extra time straightening the roots. However, root movement without crown movement is difficult to produce and some unwanted movement usually accompanies this phase such as space re-opening. It is therefore better to control tipping during the initial space closure phase and achieve as much bodily movement as possible. Forces directed through the center of resistance of teeth produces bodily movement. Because the center of resistance of teeth typically reside in alveolar bone, there is no direct way to apply forces there. However, the center of resistance can be approximated with the use of extension arms often referred to as *power arms*. These power arms extend from the archwire to approximate the center of resistance of teeth. As the point of force application moves closer to the center of resistance more controlled tipping is observed. At the center of resistance, tooth movement occurs via bodily movement. Force application beyond the center of resistance leads to preferential root movement that may be desirable in certain situations.[24] Numerically, the center of resistance of anterior teeth is believed to be greater than 8mm apical from the orthodontic bracket slot. For canines, the teeth with the longest roots, the center of resistance is believed to be around 10mm. Thus it is believed that force-to-moment ratios of greater than 8 and approaching 10 will produce bodily movement.[3] In the case of en-masse retraction for space closure, multiple teeth move as one unit and the center of resistance of that unit is more complex. Studies on epoxy models using photoelastic material have found that the center of resistance of the four maxillary incisors exists at the sagittal midline approximately 6mm apical to the alveolar crest and 4mm posterior to the facial surface of the central incisors.[25] Another study using finite element analysis predicted that the center of resistance of the six maxillary anterior teeth was 12.2mm apical to the incisal edge of the central incisor.[26] Lastly, a study on dry skulls using laser reflection technique found the center of resistance to be 7mm apical to the interproximal alveolar bone height between the central incisors.[27] Taken together these studies infer that the center of resistance of the anterior teeth segment lies about 10mm above the bracket slot.

1.6.5 The study of force systems

Designing experiments to study how forces correlate with tooth movements has been difficult for researches due to multiple complications. First, fully controlling tooth movement is difficult. Without full control, accurate correlation is weak. Second, tooth movement follows a non-linear pattern that is time dependent. This results from the underlying biology of tooth movement where a lag period precedes tooth movement. Finally, there are large variations in the rates of tooth movement between individuals that makes significant differences difficult to detect.[28] Current studies investigating of forces and space closure fall into two broad categories: 1) Measuring the rate of space closure, 2) Measuring the response of individual teeth to applied forces and movements.

Animal and human studies have measured the rate of space closure when various retraction forces were used. Measurements have primarily used calipers to directly measure the remaining space or cephalometric radiographic superimposition to measure differences in tooth positions relative to surrounding skeletal structures.[5,29] Direct measurement with calipers introduces the difficulty of resolving how much each tooth contributed to the space closure. Cephalometric radiographic superimposition measurements suffer from the difficulty of resolving superimposed structures and problems with reproducing patient position during serial radiographs. Finally, while these measurements shed light on the rate of tooth movement, they measure the tooth movement on primarily one- or two- dimensions but teeth move in three-dimensions.

The study of tooth movement in three-dimensions has evolved through the years from inventive techniques involving holograms[30] to load-cells and finite element analysis. One area where load-cells have been used to study three-dimensional tooth movement is the effect of loops and bends in archwires on teeth. As teeth move, they will undergo some combination of tipping, translation, and rotation. In anticipation of the tipping that commonly occurs during space closure, orthodontists commonly add various loops and tip-bends to archwires as a countermeasure, with the hope that the net movement will be translation. Burstone in the 1970's used load cells to measure how the design of vertical closing loops impacted force and moment-to-force ratio measurements in two-dimensions.[3] More recently, studies have used load cells to study how closing loops and T-loop gable bends generate forces and moments at teeth bordering the space closure site.[31,32] Load cells measured the forces and moments of a simulated canine and simulated second premolar, bordering a first premolar extraction site. All remaining teeth in the dental arch were part of a fixed acrylic dental model. The primary limitation of these existing load cell studies is the reduction of the force system to a unilateral two-tooth system, representing only a small segment of the dental arch. However, orthodontic space closure typically affects teeth distant to the space closure site, including the molars and the incisors, representing teeth that would not be measured in a two-tooth system. Also, space closure commonly occurs bilaterally in the dental arch.

To overcome the limitations of one or two-teeth force systems, an orthodontic simulator (OSIM) was developed that included load cells measuring forces and moments on all 14 teeth in the dental arch simultaneously.[33] Studies involving the OSIM have compared conventional ligation methods versus self-ligation methods, as well as investigated the forces acting on high canines and lingually displaced incisors.[34-36] The ability to measure all teeth simultaneously has been the major advantage of this system, but it is limited by traditional *in vitro* concerns such as lack of periodontal ligament compliance and the contribution of the oral environment to friction.

With the improvements in computer modeling, finite element analysis has been used to study forces and tooth movements in orthodontics. In this system, the various components of the dental arch are reduced to *elements* and assigned attributes that govern their behaviour such as the modulus of elasticity of teeth and bone. A computer model iterates the behaviour of the various elements acted upon by forces and track how the elements respond.[37] Whereas load-cell studies have generally been limited to one- or two- teeth systems, finite element analysis can investigate the entire dental arch. This has allowed the modeling of en-masse retraction scenarios with various techniques, such as dental anchorage versus skeletal anchorage or sliding mechanics versus loop mechanics.[38,39] One caveat is that computer modeling in finite element analysis is limited by the complexity of the system. As such, approximations are used, which decreases the accuracy of the modeling. Another limitation is that the values used in the modeling such as friction and compliance of supporting biologic structures has of yet not been determined empirically. Load cell based *in vitro* studies, as well as *in vivo* studies will continue to elucidate these values and help improve the modeling provided by finite element analysis.

1.7 Conclusion

While there have been advancements in our understanding of how applied forces correlate with tooth movements there continue to be unknowns. Traditional measures of tooth movement such as the rate of space closure quantify movement along one-dimension but in clinical settings teeth move in three-dimensions in response to forces. Unwanted movements in the vertical axis such as intrusion or extrusion often accompanies space closure, a result of the three-dimensional nature of tooth movement. Studies that have examined the nature of three-dimensional tooth movement have commonly limited the study to one- or two-teeth systems due to the natural complexity of multi-teeth force systems. However, forces often induce effects distant to the site of application, particularly in continuous archwire mechanics. Therefore, a review of the current literature highlights an existing deficiency in studies of multi-teeth systems investigating the effects of forces in three-dimensions during space closure.

2 Chapter 2: Systematic Review - En-masse retraction in orthodontic space closure.

2.1 Introduction

Closure of extraction spaces is often required in orthodontic treatment to eliminate spacing in the dental arches and improve occlusal interrelationships. First premolars are often targeted for extraction leaving an anterior segment comprised of the six anterior teeth, and two posterior segments comprised of the second premolar plus erupted molar teeth. Traditionally, retraction of the anterior segment is anchored by the two posterior segments such that retraction forces placed on the anterior segment generate protraction forces on the posterior anchorage units (called “en-masse retraction”). Conventionally, en-masse retraction utilizes retraction forces from elastomeric chains, looped archwires or retraction springs from the posterior dentition to a post on the archwire. Those protraction forces may be an undesirable side-effect to the treatment outcome if mesialization of the posterior teeth is considered unfavorable as some anchorage loss is expected using conventional en-masse retraction methods.[1] Therefore management of the posterior anchorage is crucial to orthodontic treatment in some cases of space closure.[2]
In cases where greater control of posterior anchorage is required a “2-stage retraction” approach is often used, where the canines are retracted first followed by retraction of the remaining four anterior teeth. However, the effectiveness of 2-stage retraction versus en-masse retraction has been debated with some studies suggesting no difference in anchorage control with either method.[3]

With the introduction of skeletal-based anchorage via orthodontic temporary screws, there is the potential to prevent the unwanted side-effects of en-masse retraction.[4] Although theoretically this makes sense, some studies[5,6] still showed mesialization of the posterior anchorage unit, albeit to a lesser degree than traditional en-masse retraction. In contrast, other studies[7,8] have suggested distalization of the posterior anchorage unit, which may or may not be favorable. Lastly, intrusion of the anterior segment often occurs during retraction with skeletal-based anchorage.[9]

The inability to control anchorage during orthodontic space closure can potentially increase treatment time and reduce long-term stability. If anchorage is lost then it is often difficult to recover. Additional methods such as extra-oral anchorage or skeletal anchorage could be used to restore anchorage but increased treatment time would result. Also, poor anchorage control often results in tooth crowns tipping into the extraction space during space closure, which increases treatment time because after spaces are closed roots need to be uprighted.[10] Lastly, long-term stability is believed to rely on root parallelism such that orthodontic relapse and periodontal damage is associated with poorly aligned dentition.[11] Taken together, improved anchorage control during space closure, when required, benefit both the patient and the clinician.

To the best of our knowledge there is no previous systematic review evaluating the available evidence around dental and skeletal anchorage in en-masse retraction. Therefore, the main objective of this systematic review is to compare the effectiveness of dentally-anchored versus skeletally-anchored en-masse retraction on anchorage loss during space closure.

2.2 Methods

Protocol and registration

No protocol and registration was available.

Eligibility criteria

Initial inclusion criteria were *in vivo* studies with titles or abstracts suggesting en masse retraction and orthodontic space closure. No limits were placed on patient's age or study publication year. No language limitations were set. Initial exclusion criteria were case reports and review articles. Animal studies were also excluded.

For articles that met initial eligibility criteria, once full article copies were collected, final eligibility criteria was assessed through the following PICO:

- (P)opulation: Patients who underwent tooth extraction and required orthodontic space closure.
- (I)ntervention: Space closure using orthodontic temporary screws or other form of skeletal anchorage.
- (C)omparison: Space closure using conventional dental anchorage.
- (O)utcome: Retraction distance of incisors vs. reciprocal movement of molars.

<u>Information sources</u>

Electric database searches were conducted with Ovid Medline, Ovid Embase, Scopus, Cochrane Library. No limits were placed on dates and all articles indexed up until June 1, 2014 were included.

<u>Search</u>

Search strategies specific to each database are presented in Table 2.1. Manual searches were conducted on bibliographies from retrieved articles and agreement between two authors (DL and JS) would determine final inclusion. All relevant articles were entered into RefWorks reference manager (ProQuest LLC.)

Table 2.1. Search Strategy

OVID Medline and OVID EMBASE

1	mini implant.mp.
2	micro implant.mp.
3	miniscrew.mp.
4	mini screw.mp.
5	1 or 2 or 3 or 4
6	exp Orthodontic Space Closure/
7	en masse.mp.
8	exp Tooth Movement/
9	6 or 7 or 8
10	5 and 9

Cochrane Library

(miniscrew OR mini implant OR mini screw) AND retraction

Scopus

[(miniscrew OR mini implant OR mini screw) AND retraction] OR “en masse retraction”

Study selection

Two review authors DL and JS did independently screen titles and abstracts retrieved from electronic searches and duplicates removed. Discrepancies between the included articles were discussed to determine final inclusion or exclusion status. For the second selection phase the same two reviewers participated. Discrepancies were again solved by consensus.

Data collection process

Data from articles were independently retrieved by the same two authors. Results were compared and discrepancies discussed until a final consensus was reached.

Risk of bias in individual studies

The Cochrane Collaboration tool for assessing risk of bias was used. Each domain was scored as ADEQUATE, NOT ADEQUANTE, or UNCLEAR. An overall assessment of each study was scored as Low risk of bias, Unclear risk of bias, or High risk of bias.

Summary measures

Amount of retraction space lost during space closure was determined as a proportion of the space loss over the total space available to be closed.

Synthesis of results

If the available information warranted it a meta-analysis was planned.

Risk of bias across studies

If a meta-analysis was possible risk of bias across the included studies was planned.

2.3 Results

Study selection

The search strategy results are presented in a flowchart (Fig 2.1). Eleven full-text articles were reviewed in the second selection phase of which eight were later excluded. Reasons for exclusion at this stage can be found in Table 2.2. Therefore, only three articles met the final inclusion/exclusion criteria and were finally included.

Figure 2.1. Search flowchart.

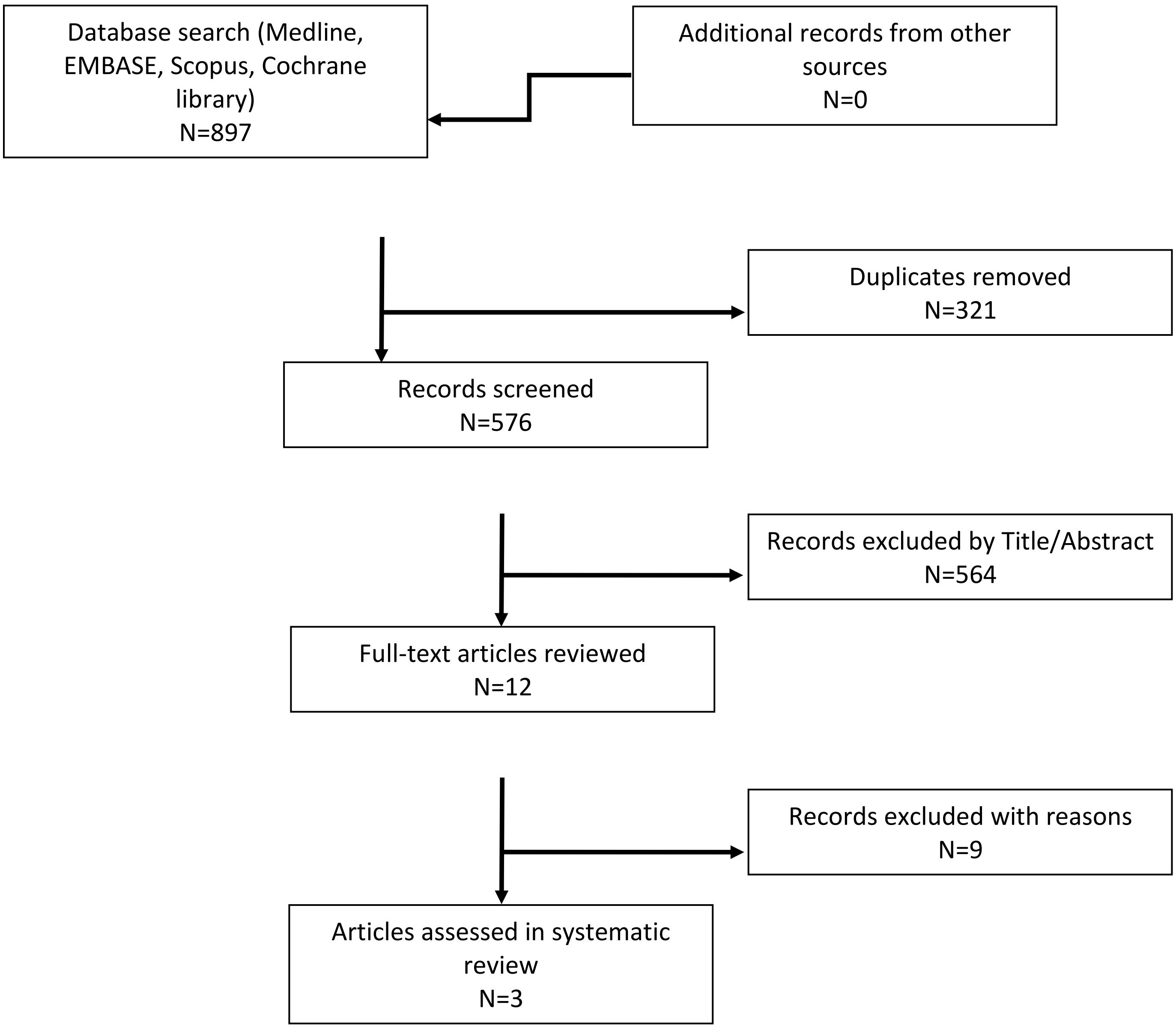

Table 2.2. Excluded Studies

	Study	Reason
1	Basha et al.[12]	Use of extra-oral anchorage
2	Kuroda et al.[6]	Use of extra-oral anchorage
3	Lai et al.[13]	Use of extra-oral anchorage
4	Lee et al.[14]	Indirect anchorage
5	Park et al.[15]	Use of extra-oral anchorage
6	Upadhyay et al. (2008a)[8]	Use of extra-oral anchorage
7	Upadhyay et al. (2008b)[16]	Use of extra-oral anchorage
8	Yao et al.[17]	Use of extra-oral anchorage
9	Lee et al.[18]	Use of extra-oral anchorage

<u>Study characteristics</u>

Table 2.3. Study Characteristics

		Liu et al. (2009)	**Al-Sibaie et al. (2014)**	**Victor et al. (2014)**
# Participants (Control/Intervention)		17 / 17	28 / 28	10 / 10
Mean age (years) (Control/Intervention)		19.71 / 21.65	20.46 / 23.02	N.S. / N.S.
Orthodontic temporary screw group	Anchorage	8-10mm above archwire between maxillary second premolar and molar	8-10mm above archwire between maxillary second premolar and molar	8mm above archwire between maxillary second premolar and molar
	Force	N.S.	150g per side	150g per side
	Archwire during retraction	0.019 x 0.025 SS	0.019 x 0.025 SS	0.019 x 0.025 SS
	Retraction method	Elastomeric chain from mini-implant to posted-archwire	Elastomeric chain from mini-implant to posted-archwire	NiTi closed coil from mini-implant

				to posted-archwire
Control group	Anchorage	Maxillary TPA	Maxillary TPA	Maxillary TPA
	Force	N.S.	N.S.	150g per side
	Archwire	0.019 x 0.025 SS	0.019 x 0.025 SS	0.019 x 0.025 SS
	Retraction method	En-masse retraction. Elastomeric chain from molar hook to posted-archwire	Two-stage retraction with elastomeric chain.	En-masse retraction. NiTi closed coil from molar hook to posted-archwire
Recall interval		N.S.	3 weeks	4 weeks

TPA = transpalatal arch

N.S. = Not specified.

<u>Risk of bias within studies</u>

The risk of bias is presented below in Table 2.4. No study presented with low risk of bias, two studies had unclear risk of bias, and one study had low-to-unclear risk of bias.

Table 2.4. Risk of Bias

	Liu et al (2009)	Al-Sibaie et al (2014)	Victor et al (2014)
Sequence generation	Randomization via random number table. ADEQUATE	Computer-generated randomization list. ADEQUATE	Authors state patients were randomized to two groups (N=10 each). No mention of sequence generation method. UNCLEAR
Allocation concealment	Not stated. UNCLEAR	Sequentially numbered opaque and sealed envelopes used. ADEQUATE	Not stated. UNCLEAR
Blinding of participants, personnel and outcome assessors	Personnel not blinded during procedure, but this is difficult to achieve due to type of procedure. No blinding during analysis of data.	Not stated. UNCLEAR	Personnel not blinded during procedure, but this is difficult to achieve due to type of procedure. No blinding during analysis of data.

	NOT ADEQUATE		NOT ADEQUATE
Incomplete outcome data	No indication if patients were lost to follow-up. UNCLEAR	Reported no patients lost to follow-up. ADEQUATE	No indication if patients were lost to follow-up. UNCLEAR
Selective outcome reporting	Eight orthodontic temporary screws failed and were replaced after 2 months. This was not considered in the analysis. NOT ADEQUATE	Three orthodontic temporary screws failed and were replaced. Not noted when. This was not considered in the analysis. NOT ADEQAUTE	No indication of orthodontic temporary screws failures. UNCLEAR
Other sources of bias	Cephalometric radiograph measurement error possibly introduces bias in outcome measures and no error of method provided. UNCLEAR	Cephalometric radiograph measurement error was assessed according to Dahlberg's formula ADEQUATE	Cephalometric radiograph measurement error possibly introduces bias in outcome measures and no error of method provided. UNCLEAR
	UNCLEAR	UNCLEAR	UNCLEAR

Results of individual studies

The results of the individual studies are presented below in Table 2.5. There was general agreement between the studies that orthodontic temporary screws decreased loss of posterior anchorage. There was some disagreement on whether orthodontic temporary screws reduced treatment time, reduced extrusion of molars, or reduced incisor tipping.

Table 2.5. Study Results

Author	Treatment Time (months)	Incisor Movement	Molar Movement	Percentage Anchorage loss	Author's conclusion
Liu et al.[19] (2009)	26.88 ± 6.54 (controls) vs. 25.65 ± 5.06 (mini-	Retraction[¥] (mm): -4.76 ± 1.67 (controls) vs. -7.03 ± 1.99 (orthodontic	Horizontal change[¥] (mm): 1.47 ± 1.15 (controls) vs. -0.06 ± 1.40 (orthodontic temporary	Control: 23.60% Orthodontic temporary screw: -0.86%	1) No statistical difference in treatment time between groups. 2) Greater statistical

	implant) P=0.542	temporary screws) P<0.01 Tipping (°): -12.03 ± 8.07 (controls) vs. -13.53 ± 6.16 P=0.547	screws) P<0.01 Vertical Change[§] (mm): 1.91 ± 1.75 (controls) vs. -1.42 ± 2.55 (mini-implants) P<0.01		incisor retraction with orthodontic temporary screws, but no difference in tipping 3) Less molar mesialization and less molar extrusion with orthodontic temporary screws
Al-Sibiae et al.[20] (2014)	16.97 (controls) vs. 12.90 (mini-implant) No P-Value or SD provided	Retraction[¥] (mm): -3.48 ± 2.51 (controls) vs. -4.48 ± 1.28 (orthodontic temporary screws) P=0.009 Tipping (°): -5.70 ± 2.28 (controls) vs. -1.96 ± 0.82 (orthodontic temporary screws) P<0.001	Horizontal change[¥] (mm): 1.50 ± 1.25 (controls) vs. -0.89 ± 0.59 (orthodontic temporary screws) P<0.001 Vertical Change[§] (mm): 0.06 ± 0.68 (controls) vs. -0.25 ± 0.83 (orthodontic temporary screws) P=0.231	Control: 30.12% Orthodontic temporary screw: -24.79%	1) Possible shorter treatment time en-masse retraction with orthodontic temporary screws than 2-stage retraction without orthodontic temporary screws 2) Greater statistical incisor retraction and less tipping with orthodontic temporary screws 3) Less molar mesialization with orthodontic temporary screws. No statistical difference in

					vertical movement.
Victor et al.[21] (2014)	Not Specified	Retraction: Not specified Tipping (^{O}): 5.8 ± 1.3 (controls) vs. 5.8 ± 1.3 (orthodontic temporary screws) P=1.00	Horizontal change: Not specified Vertical Change§ (mm): 0.8 ± 0.9 (controls) vs. -0.3 ± 0.5 (orthodontic temporary screws) P=0.01	Not measurable based on available data	1) No statistical difference in incisor tipping 2) No statistical difference in tipping between control group and orthodontic temporary screws group 3) Less extrusion in orthodontic temporary screws group

Synthesis of results

Based on available information, a meta-analysis was not feasible as the three treatment protocols differed.

Risk of bias across studies

Based on available information, risk of bias across studies analysis was not feasible as the three treatment protocols differed.

2.4 Discussion

Summary of evidence

This systematic review aimed to analyze differences in incisor and molar movements during en-masse space closure with dental anchorage or orthodontic temporary screw-based skeletal anchorage. There was no agreement on whether treatment times were affected by use of dental anchorage or skeletal anchorage as one study showed no statistical difference[7], while another study appeared to show that skeletally-anchored en-masse retraction was potentially shorter than dentally-anchored 2-stage retraction.[20] It has been reported that the rate of retraction does not vary statistically between dentally-anchored or skeletally-anchored retraction, which would support the argument of no statistically significant differences in treatment time.[22] However, it is important to note that the period of en-masse retraction is only a portion of the total treatment time such that statistical differences in retraction times may not result in a statistically different overall treatment time. Furthermore, orthodontic temporary screw failure is not uncommon which increases treatment time due to the time required for tissue healing and the time required for replacement of lost screws.[7,20,23]

Two of the papers reviewed are in agreement that skeletal-anchorage via orthodontic temporary screws increases the total distance of incisor retraction when compared with dental-anchorage. One paper[7] reported that skeletal-anchorage retracted incisors by 7.03±1.99mm versus 4.76±1.67mm in dental-anchorage, an increase of 2.27mm. The other paper[20] reported 4.48±1.28mm versus 3.48±2.51mm retraction, an increase of 1.00mm. These values correspond to an improvement of 48% and 29% of the total retraction distance when utilizing temporary screws compared with controls. However, the absolute change of 1.00mm-2.27mm may have weaker clinical implications since 1mm of change may or may not impact treatment.

Management of anchorage loss due to molar mesialization is a common consideration in orthodontic treatment. About 1/3 of the extraction space is expected to be used up by anchorage loss when dental-anchorage is employed.[24] This was reflected in the control groups of the included studies. In cases where mesial movement of molars is deleterious, reducing anchorage loss is beneficial. Two papers in this review reported a statistically significant reduction in anchorage loss when using orthodontic temporary screws. In one paper, virtually no mesial-distal movement was measured in molars with skeletal-anchorage, whereas dental-anchorage resulted in an average loss of 1.47±1.15mm.[7] The other paper reported a relative distal movement of molars when utilizing skeletal-anchorage, with dental-anchorage losing on average 1.50±1.25mm.[20] These values correspond to 23.60% and 30.12% of the extraction space that was not lost when orthodontic temporary screws were used. The finding of distal movement of the molars has been speculated to be due to continued retraction forces applied to the dental arch after the space have been closed resulting in net inter-dental forces in a distal vector.[23] In contrast, other studies have measured mesial movement of molars post-treatment in skeletal-anchored retraction groups and have attributed this finding to natural mesial drift of the molars into the extraction space during the alignment and leveling phase.[25]

During dental-anchored retraction incisors and molars tend to tip into the extraction space as well as molars often extrude to some degree. For skeletal-anchored retraction, because the temporary orthodontic screws are placed 8-10mm above the archwire, different vertical forces and moments are applied to the teeth when compared with dental-anchorage. Two papers[7,26] did not report any statistical difference in incisor tipping during retraction, while one paper[20] reported statistical significant reduction in tipping when skeletal-anchorage was used. All three papers reported mild intrusion of the molars, although one paper reported this change was not statistically significant. These findings suggest that in cases where molar extrusion is undesirable such as in open bite cases, the use of orthodontic temporary screws for retraction may have a beneficial auxiliary effect. The evidence that orthodontic temporary screws prevent incisor tipping is weaker, but may suggest the use of temporary screws to prevent unwanted incisor tipping. The relatively short treatment time during retraction may limit the potential of more significant results.

Limitations

None of the included studies had low risk of bias, with all three studies containing unclear or not adequate risk of bias. A limitation presented in two of the three studies[7,20], but not discussed in the third study[26] was failure of the orthodontic temporary screws. The negative side-effects associated with temporary screw failure, such as loss of force control and lost treatment time, can be difficult to quantify. In some cases, localized inflammation prevented immediate replacement of the temporary screws resulting in 2 months of lost treatment time.[7] In all cases, replacement of the temporary screws had to be in an adjacent location to the original screw, which theoretically would change the vector of forces applied midway through retraction treatment. None of the reviewed papers addressed the impact of orthodontic screw failure on the outcome measures of treatment time and tooth movements.

All three papers utilized lateral cephalometric radiograph measurements to determine changes in tooth position. Measurement error on cephalometric radiographs can result from superimposition of structures, mixed reliability in reproducing specific tracing points, and magnification distortion. Two separate papers published by the same research group quantified changes in tooth position after retraction, with one paper using lateral cephalograms to measure changes[27], and the other paper using 3D model analysis.[13] Their conclusion was that 3D modelling resulted in less linear measurement error. Cephalogram measurements tended to be larger than 3D modelling measurements suggesting an over-reporting of tooth position changes on cephalograms. The authors stated that magnification distortion may be the culprit for the measurement error.

Additional clinical trials with low risk of bias are needed to strengthen the level of evidence.

Clinical implications

Orthodontic temporary screw insertion contains inherent risks to the patient including infection risk, bleeding risk, and soft and hard tissue damage. Therefore, it is important to consider whether the benefits outweigh the risks before employing their use. Reported differences in anchorage loss range from 1-2mm between dental-anchored retraction and skeletal-anchored retraction. While those values are statistically significant, their clinical significance will vary based on the particular treatment case. Additionally, it is important to keep in mind the secondary effects of skeletal-anchored retraction, such as possible molar intrusion, incisor intrusion, or molar distalization. Careful consideration should be placed on whether these secondary effects are beneficial to the treatment or have to be managed.

2.5 Conclusions

Due to the limited level of evidence available, caution should be taken when considering the following conclusions.

- Use of orthodontic temporary screws does not appear to alter total treatment time.
- Anchorage loss is reduced when using orthodontic temporary screws for retraction, but absolute control is difficult to achieve as some mesialization or distalization may occur.
- Some increase in incisor retraction is expected when using orthodontic temporary screws for retraction, but control of incisor tipping is unclear.

3 Chapter 3:

Initial forces experienced by the anterior and posterior teeth during dental-anchored or skeletal-anchored en-masse retraction in an *in vitro* dental arch.

3.1 Introduction

Orthodontic treatment of cases involving severe dental crowding or severe dental protrusion often require the extraction of teeth to correct the malocclusion. First premolars are often targeted for extraction leaving an anterior segment comprised of the six anterior teeth, and two posterior segments comprised of the second premolar plus erupted molar teeth (Fig 3.1).

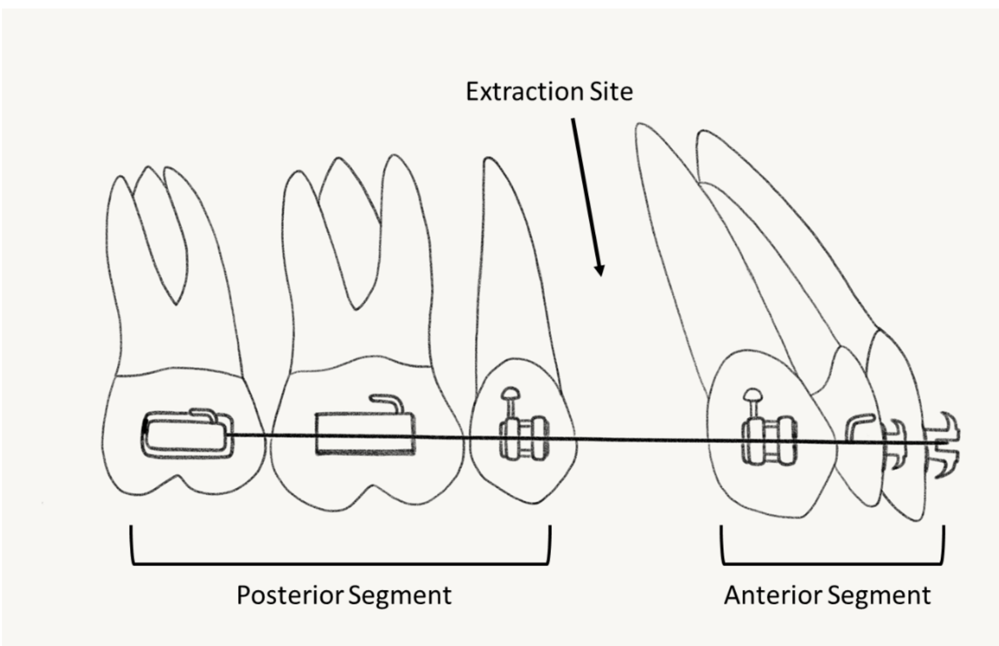

Figure 3.1. En Masse Retraction.

Space closure forces are typically generated from elastomeric chains, looped archwires, or retraction springs. In the traditional “en-masse retraction” setup, the springs or chains are directly connected to both the anterior segment and the posterior segment. This will create retraction forces acting on the anterior segment while creating protraction forces acting on the posterior segment (Fig 3.2).

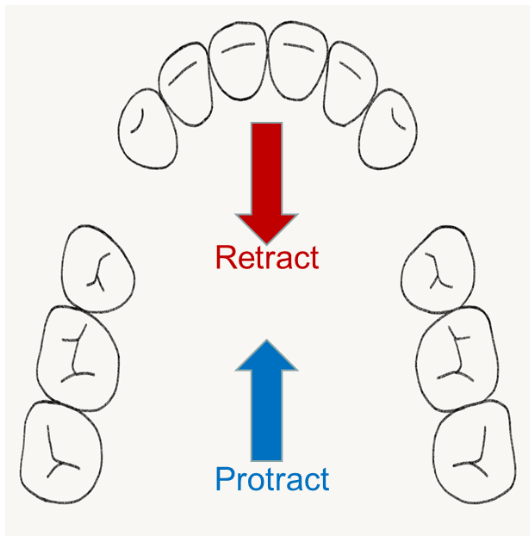

Figure 3.2. En-masse retraction and protraction forces.

Those protraction forces may be an undesirable side-effect to the treatment outcome if mesialization of the posterior teeth is considered unfavorable as some anchorage loss is expected using conventional en-masse retraction methods.[1] Therefore management of the posterior anchorage is crucial to orthodontic treatment in some cases of space closure.[2] With the introduction of skeletal-based anchorage via orthodontic temporary screws, there is the potential to prevent the unwanted side-effects of en-masse retraction.[3] Although theoretically this makes sense, some studies[4,5] still showed mesialization of the posterior anchorage unit, albeit to a lesser degree than traditional en-masse retraction. In contrast, other studies[6,7] have suggested distalization of the posterior anchorage unit, which may or may not be favorable. Lastly, intrusion of the anterior segment often occurs during retraction with skeletal-based anchorage.[8]

The inability to control anchorage during orthodontic space closure can potentially compromise treatment results. Anchorage can be difficult to recover once it is lost. Additional methods such as extra-oral anchorage or skeletal anchorage could be used to restore anchorage but increased treatment time would result. Also, poor anchorage control often results in tooth crowns tipping into the extraction space during space closure, which increases treatment time because after spaces are closed roots need to be uprighted.[9] Lastly, long-term stability is believed to rely on root parallelism such that orthodontic relapse and periodontal damage is associated with poorly aligned dentition.[10]

En-masse retraction studies have traditionally evaluated rates of tooth movement in vivo. Measurements of tooth movements have relied on cephalometric measurements[11,12], and dental cast measurements[13,14], where forces applied to teeth are measured via force gauges.[15] Due to the inherent difficulty in accurate force measurements in vivo, studies evaluating forces applied to teeth typically utilize in vitro or numerical methods. Two techniques are most often employed which are force load cells[16,17], or finite element analysis.[18-20] The limitations of previous force load cell studies used to investigate retraction mechanics are that they have only looked at single-tooth or two-tooth systems.[21,22] The limitations of finite element analysis studies are the validity of the modelling, since 3-dimensional forces applied to multi-tooth systems is currently not well understood.

The purpose of this study was to investigate 3-dimensional forces applied to a representative fourteen-tooth maxillary dentition system at the initial stages of en-masse retraction and to compare the forces delivered by conventional dental-anchorage versus skeletal-anchorage.

3.2 Materials and Methods

3.2.1 Orthodontic materials

A set of 14 orthodontic brackets (Damon Q, Ormco, Orange, CA) corresponding to 14 teeth in the maxillary dental arch were used. Each bracket was carefully positioned using a mounting jig and bonded to an individual stainless steel posts using epoxy resin. All experiments were conducted using 0.019" x 0.025" stainless steel archwire (Ormco, Orange, CA). Archwire posts were pre-soldered by the manufacturer whereas power arms were crimped onto the archwire. Retraction forces were generated using NiTi retraction springs. Two 15mm light springs (Ormco, wire diameter 0.010, coil diameter 0.030, Part # 704-6042) were used, one on the left side and one on the right side and activated to approximately 150g (1.5N) per side based on force gauge reading.

3.2.2 Orthodontic simulator (OSIM)

Force measurements were carried out using the Orthodontic Simulator (OSIM) device, which was developed and validated at the University of Alberta.[23,24] The stainless steel posts representing the individual teeth in the dental arch were connected to load-cells using custom tooth adapters. Six-axis load cells measured the forces acting on each tooth in three-dimensions (ATI Industrial Automation Nano17®). The load cells had maximum ratings of 25N along the transverse axes, and 35N along the axial axis with error measurements of 1.00%. Maximum ratings for moments were 250 Nmm along all three axes with errors ranging from 1.50%-1.75%. All force and moment measurements were recorded at the level of the load cell, which had a different coordinate system than the tooth. To determine the forces acting at the level of the bracket, the accurate position of the brackets and load cells were recorded using a FARO arm (Faro Technologies, Lake Mary, Fla). A Jacobian transformation utilizing a series of transformation matrices was used to convert the forces/moments detected at the load cell to the forces/moments that acted at the level of the bracket with the appropriate bracket coordinate system.[24]

Two software packages were used with the OSIM to conduct the experiments. The first was a LabView program (National Instruments, Austin, Tex) that allowed calibrations to be applied to the acquired data, as well as the control of data sampling. The second was written in MATLAB programming environment (MathWorks, Natick, Mass) to provide a graphical display of the force and moment data. This second program (Fig 3.3) produced two sets of vectors for each tooth. Red arrows denoted the net forces experienced by that tooth, while blue arrows represented net moments experienced by that tooth at the bracket. The length of each arrow was proportional to the magnitude of that force/moment. Teeth experiencing a net force of greater than or equal to 1N were coloured red to distinguish them from the remaining teeth. This system served as a quick visual reference means to evaluate the loads acting throughout the arch.[23,24]

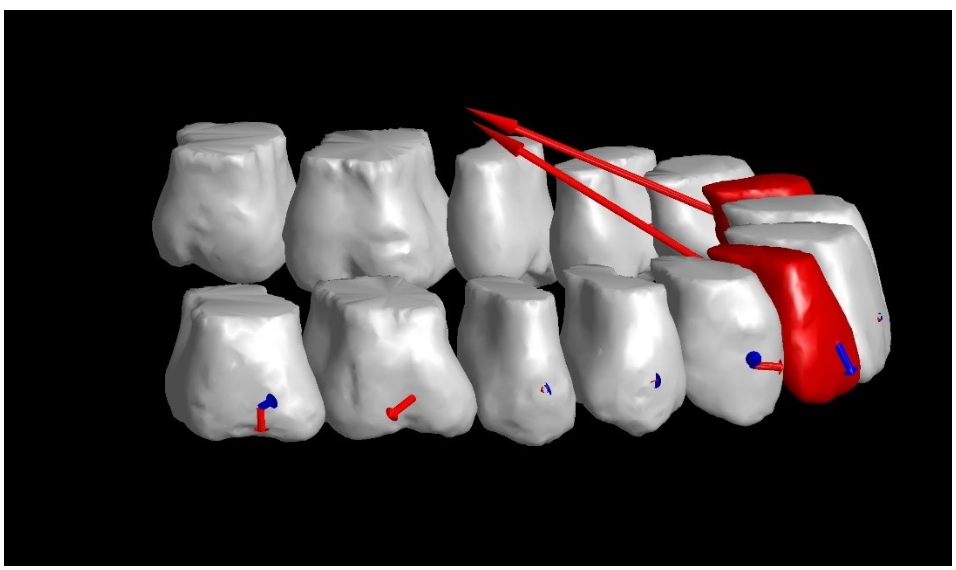

Figure 3.3. OSIM visual reference for loads acting around the arch.

A custom platform was created for the OSIM to provide a skeletal mini screw attachment point (Fig 3.4). It was designed to be both rigid and also secured to the base of the OSIM in order to minimize transferring forces to the load cells. The upper translation stage was positioned on a rail that allowed it to be moved along the anterior and posterior directions to achieve the ideal horizontal position, which was chosen to be between the second premolar and the first molar, at which point that position was secured by a screw. Finally, the vertical position could be controlled by a third platform controlled by a screw with the chosen position approximately 8mm above the archwire. With the custom arms in the desired position, they were secured using screws to create an attachment point for the retraction springs.

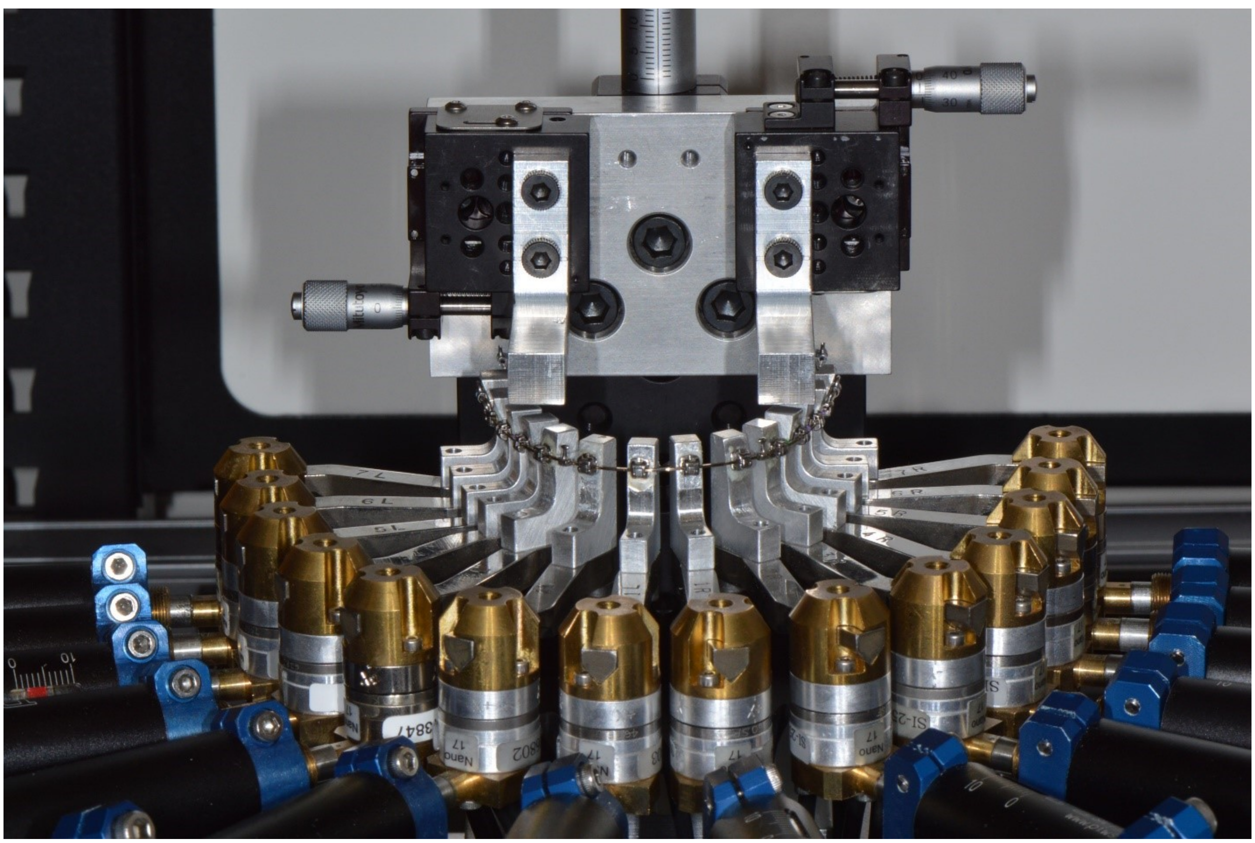

Figure 3.4. Skeletal mini screw platform for OSIM.

All tests were carried out in a temperature controlled chamber that was set to 37° Celsius to represent the approximate temperature in the oral cavity. All testing materials were allowed to equilibrate to this temperature prior to running any tests. Prior to testing, a zeroing procedure was carried out to minimize forces acting on the system during the experiment. The zeroing procedure involved the real-time display of force/moment data using the OSIM software as the archwire was progressively ligated into the dental arch starting from the anterior teeth back to the posterior teeth.[23,24] Starting from the central incisor brackets, the archwire was ligated and the horizontal and vertical micrometers used to move those brackets until the real-time output of forces and moments was sufficiently low implying those brackets were in a passive position. An upper limit of < 0.1N was set for each load cell during this initialization phase. Once the central incisor brackets met the limit criteria, the lateral incisor brackets were ligated and the zeroing procedure was completed for those brackets. This procedure was carried out until all brackets were under the upper limit and the arch was deemed sufficiently zeroed. At this point the load cells were "biased" such that all force and moment readings were zero prior to applying the forces. The effects of zeroing the load cells prior to each test is discussed in more detail in the appendix (Appendix A: sensitivity study).

3.2.3 Test setup

Three treatment groups were compared in this study (Fig 3.5):

Group 1) Conventional dentally-anchored retraction using posted archwire

Group 2) Conventional skeletally-anchored retraction using posted archwire

Group 3) Skeletally-anchored retraction using archwire power arms.

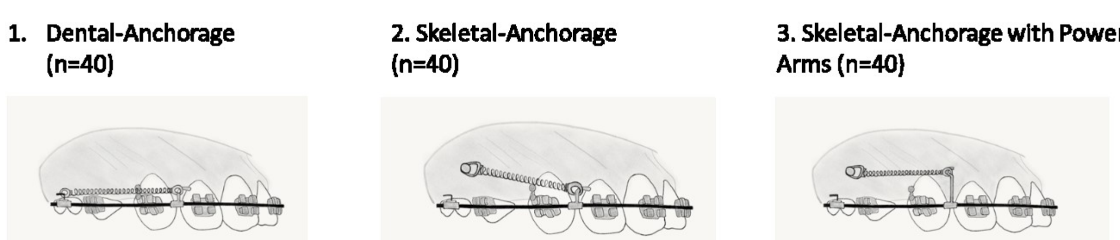

Figure 3.5. Treatment groups.

In group 1, retraction springs were connected from the hook on the first molar bracket to the archwire post on the same side (Fig 3.6). In group 2, retraction springs were connected from a fixed point mimicking a skeletal mini screw placed between the first molar and the second premolar to the archwire post on the same side (Fig 3.7). The mini screw was placed 8mm above the archwire, midway between the second premolar and the first molar. In group 3, archwire power arms (Power hook triple cast split crimpable, American Ortho, Sheboygan, Wisconsin) were crimped onto a 0.019" x 0.025" SS archwire in the same position as the previous archwire posts (Fig 3.8). The power arms provided three attachment points of 4mm, 7mm, and 10mm. The 10mm height attachment point was used as it best approximated the center of resistance of the anterior teeth segment.

In all tests, an extraction setup was simulated by removing the left and right first premolars from the arch. The brackets representing the first premolars were removed from the arch so that they did not interact with the archwire during testing phases. The remaining teeth were grouped into two segments: 1) *Anterior teeth segment*, which was represented by the 6 anterior teeth (1.3 / 1.2 / 1.1 / 2.1 / 2.2 / 2.3) and 2) *Posterior anchor segment*, represented by the posterior teeth, 3 per side, bilaterally (1.7 / 1.6 / 1.5 // 2.5 / 2.6 / 2.7).

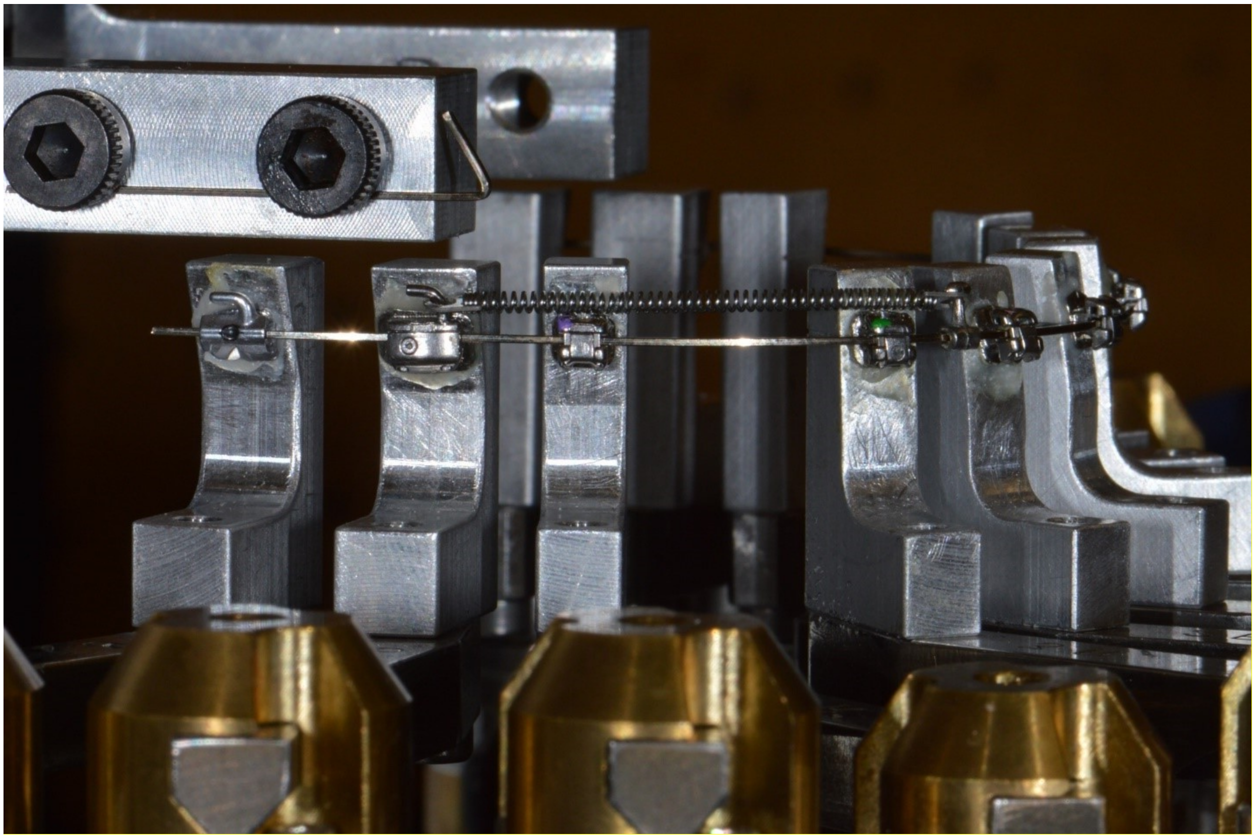

Figure 3.6. OSIM setup for dental retraction.

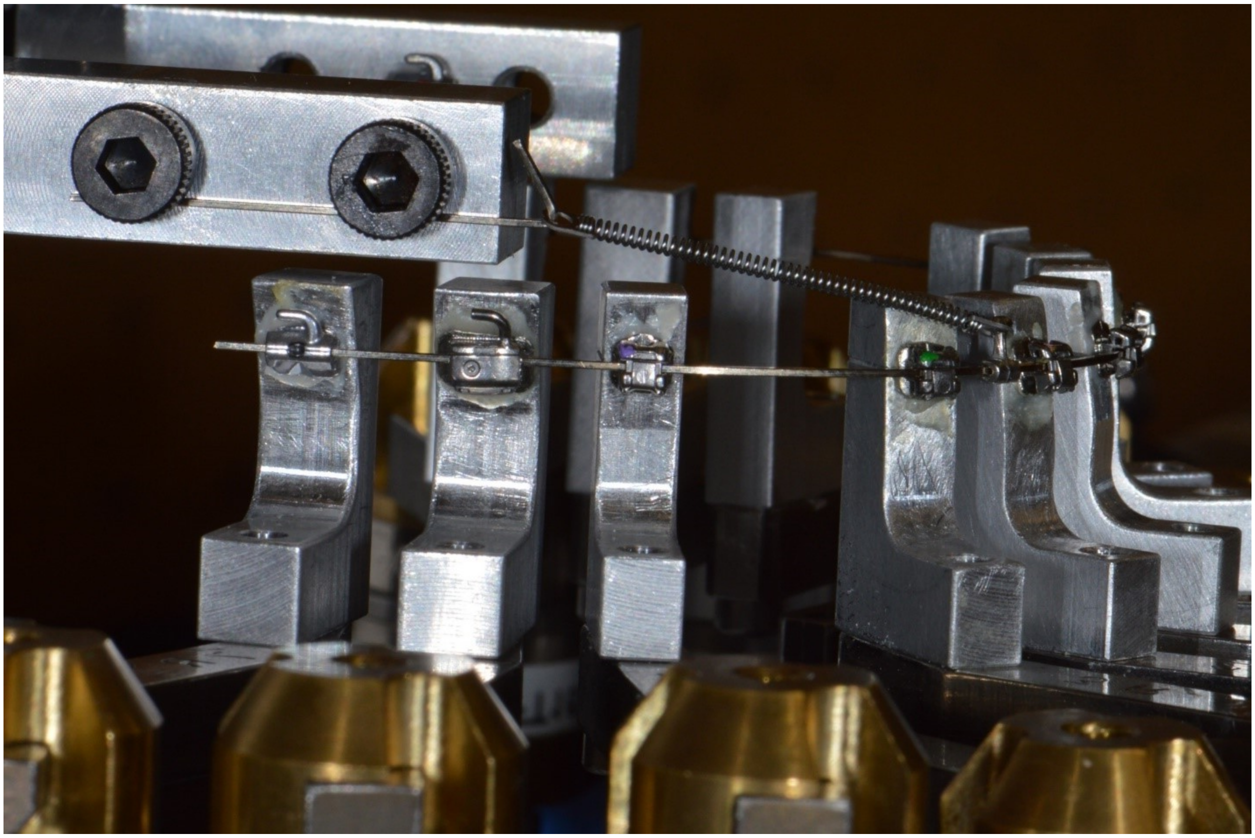

Figure 3.7. OSIM setup for skeletal retraction.

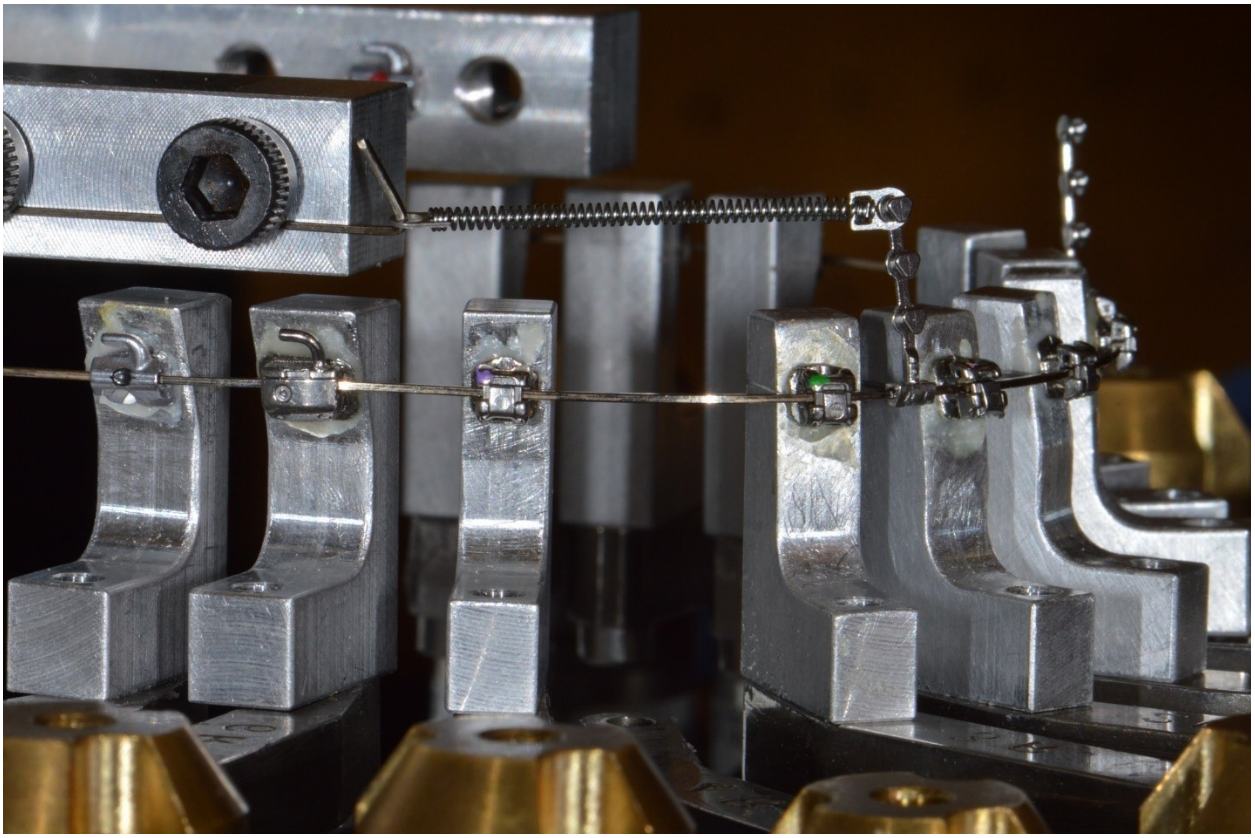

Figure 3.8. OSIM setup for skeletal retraction with power arms.

3.2.4 Force measurements

Sample size was calculated using a confidence interval of 95% and margin of error (ME) of 0.05N. A pilot study was carried out to determine sample variance (s), which was found to be 0.165N. The sample size equation was used to determine and an N=40 was determined (t~z = 1.96).

$$n = \left(\frac{t * s}{ME}\right)^2$$

Force and moment measurements were acquired along three axes (x-, y-, z-axis) represented by Fx, Fy, Fz for forces and Mx, My, Mz for moments. Fx represented the mesial-distal force, Fy represented the buccal-lingual force, and Fz represented the intrusion/extrusion force (Fig 3.9). Prior to each test run, baseline forces were sampled 50 times over approximately 10 seconds without retraction springs and averaged. The springs were then engaged according to a randomized test order for groups 1 and 2 and again sampled 50 times and averaged. Group 3 tests were not randomized due to the need to switch archwires but were still sampled 50 times and averaged. Forces along all three axes were taken to be the difference between the active spring force and the baseline force for that axis.

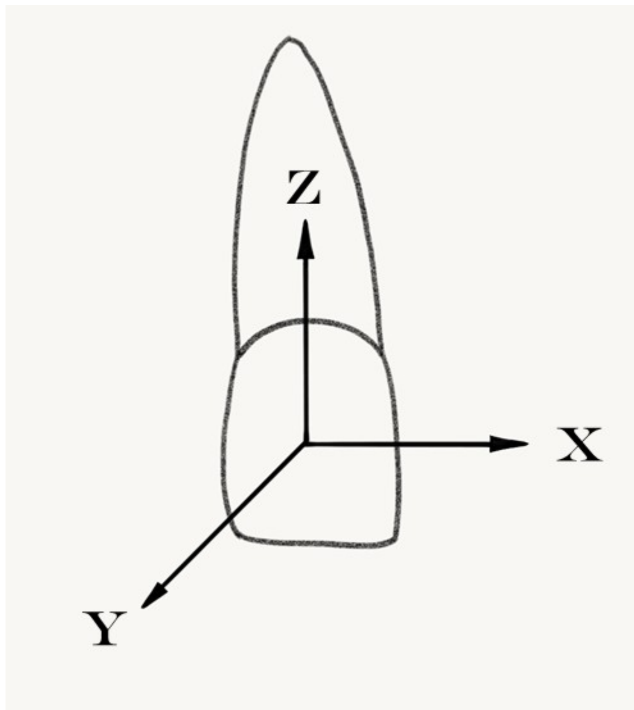

Figure 3.9. Dental force axes.

Because the direction of the buccal-lingual axis (y-axis) and the mesial-distal axis (x-axis) varied by tooth along the dental arch, multiple teeth could not be directly compared. Thus a single antero-posterior axis was chosen, which reflected the overall antero-posterior axis of the dental arch. The component of force along this antero-posterior axis was calculated for each tooth. Retraction forces for each tooth in the anterior teeth segment were summed to yield a total anterior retraction force. Protraction forces for the posterior segment were also summed and compared. Because the z-axis did not change throughout the arch, no further calculations were required and Fz was directly used.

3.2.5 Statistical analysis

Statistics were carried out using IBM's SPSS v22 software (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp). A statistical significance level of $\alpha = 0.05$ was chosen for all testing. Multivariate analysis of variance (MANOVA) was used to determine differences between treatment groups on the 3-dimensional forces acting on the anterior teeth segment and posterior teeth segment. Assumption testing was carried out using box plots for normality, matrix scatter plots for relationship between dependent variables, and Box's Test for equality of covariance matrices. Greenhouse-Geisser correction was used for multivariate hypothesis testing. A Tamhane correction was used where applicable during post hoc testing.

3.3 Results

3.3.1 Forces acting on the anterior teeth segment.

The six anterior teeth (1.3 / 1.2 / 1.1 / 2.1 / 2.2 / 2.3) were treated as one unit termed the "anterior teeth segment". Retraction forces measured by each load cell in the segment were summed to generate a total retraction force corresponding to the entire anterior teeth segment. The summed force was then compared between the three treatment groups.

The OSIM software transferred loads measured by the load cells to a coordinate system that aligned Fx with the archwire in the mesial-distal direction. To determine an overall retraction force for the anterior teeth segment the component of force from each tooth in the anterior teeth segment was calculated along the single anterior-posterior axis (Fig 3.10). The resultant anterior-posterior force from each tooth was given the term F_{distal} or F_d, and the sum of all the F_d in the anterior segment was termed F_dSUM.

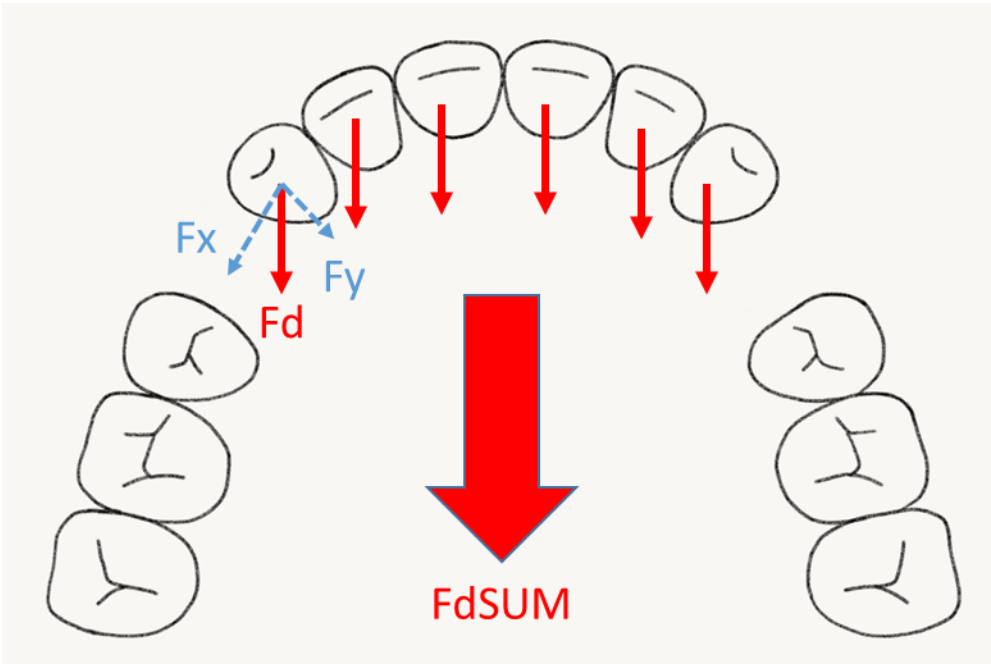

Figure 3.10. Retraction axis.

3.3.2 Retraction forces experienced by the anterior teeth segment

Within the dentally-anchored group, retraction springs generated a retraction force of F_dSUM = 2.99 ± 0.27N with 95% CI [2.91, 3.07]. Skeletal-anchorage retraction produced similar forces F_dSUM = 3.05 ± 0.14N with 95% CI [2.98, 3.13] that was not significantly different from the dentally-anchored group ($p = 0.49$). The addition of archwire power arms to skeletal-anchorage retraction significantly increased retraction forces to F_dSUM = 3.30 ± 0.30N with 95% CI [3.22, 3.37] ($p < 0.001$). This retraction force was also significantly higher when compared with dental-anchorage ($p < 0.001$) (Fig 3.11).

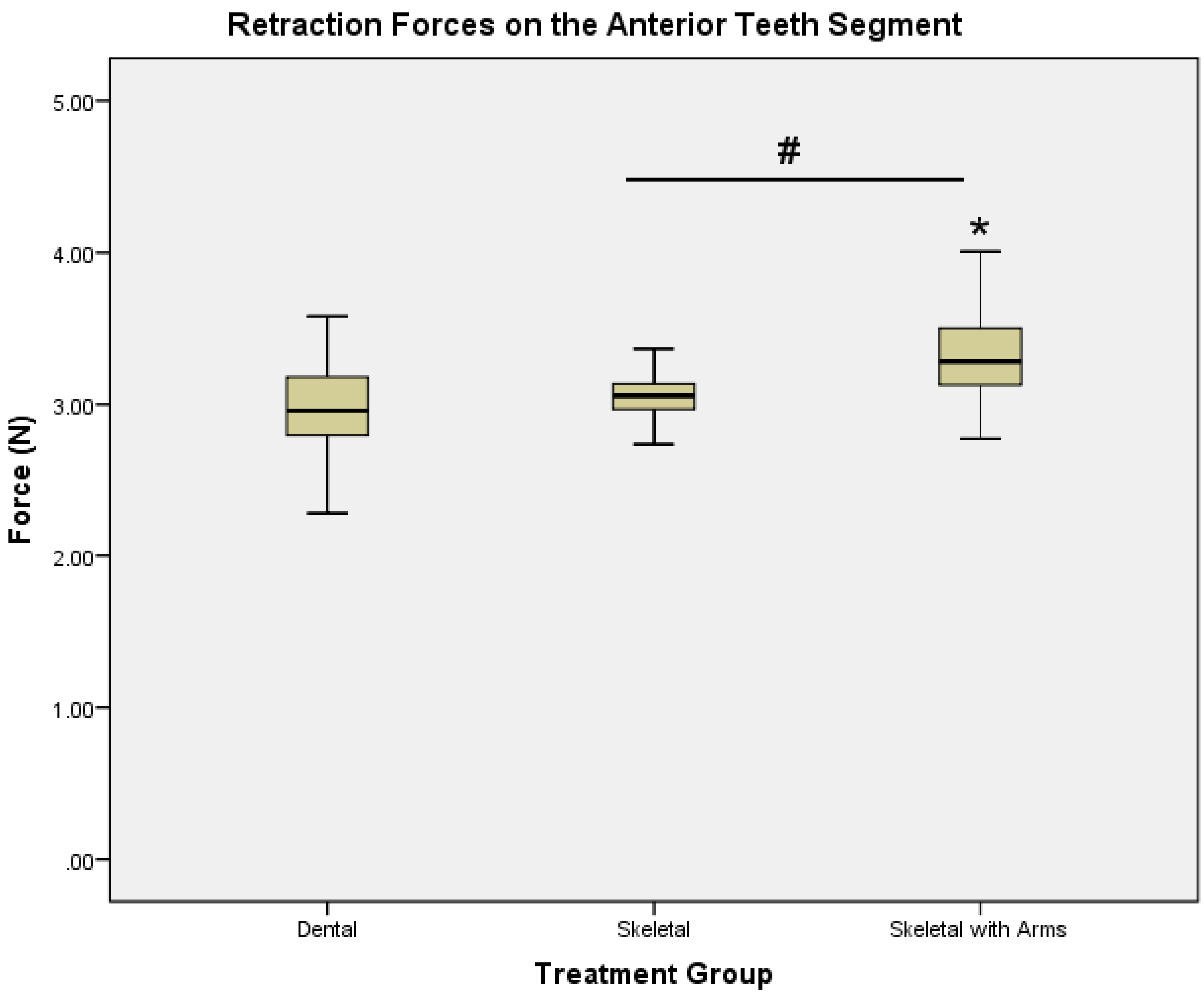

Figure 3.11. Comparison of retraction forces experienced by the anterior teeth segment. (*) denotes difference to 'Dental' group ($p < 0.001$). (#) $p < 0.001$.

3.3.3 Vertical forces experienced by the anterior teeth segment

Within the dentally-anchored group, retraction springs generated a vertical force of 0.01 ± 0.07N with 95% CI [-0.02, 0.04]. Skeletal-anchorage significantly increased the vertical force to 0.98 ± 0.70N with 95% CI [0.95, 1.01] ($p < 0.001$). The addition of archwire power arms to skeletal-anchorage retraction significantly reduced the vertical forces to 0.57 ± 0.11N with 95%

CI [0.54, 0.60] ($p < 0.001$), but this vertical force was still significantly higher when compared with dental-anchorage ($p < 0.001$) (Fig 3.12).

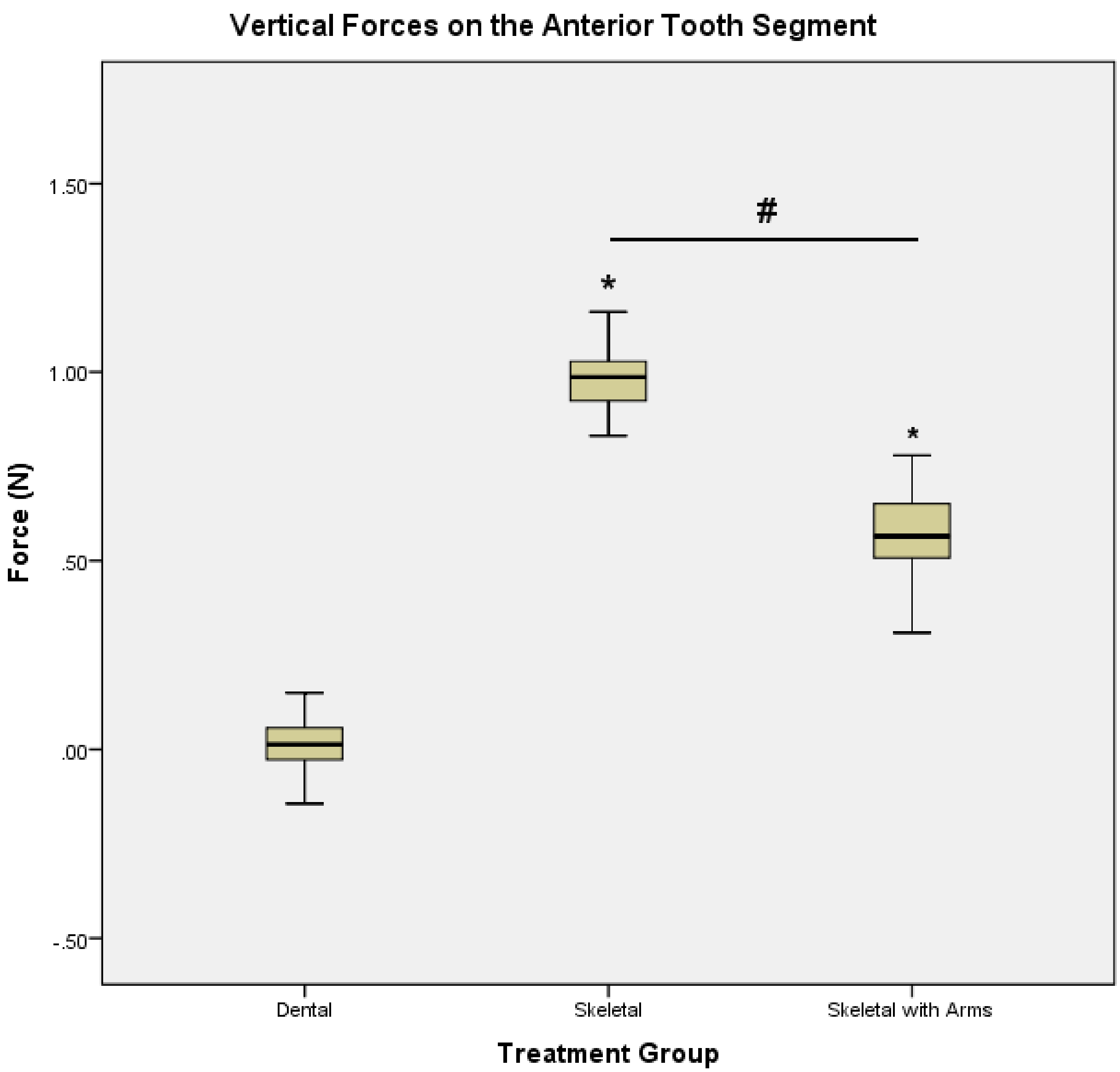

Figure 3.12. Comparison of vertical forces experienced by the anterior teeth segment. (*) denotes difference to 'Dental' group (p < 0.001). (#) p < 0.001.

3.3.4 Forces acting on the posterior anchor segment

To compare the forces placed on the posterior anchorage unit between the three treatment groups, the sum of the forces of the right posterior teeth (teeth 1.5 / 1.6 / 1.7) were averaged with the sum of the forces of the left posterior teeth (teeth 2.5 / 2.6/ 2.7). Protraction forces, buccal-palatal forces, and vertical forces were then compared between the three treatment groups.

3.3.5 Protraction forces on the posterior teeth

Traditional dental-anchorage engages the retraction springs directly on the first molars. This setup generated the largest protraction forces of 1.77 ± 0.10N per side with 95% CI [1.75, 1.80]. By engaging the retraction spring on a fixed skeletal anchor point instead of the first molar, the protraction forces experienced by the first molars was reduced to virtually zero 0.05 ± 0.08N per side with 95% CI [0.03, 0.07] ($p < 0.001$). The addition of archwire power arms to skeletal-anchorage retraction maintained virtually zero protraction forces on the first molars -0.01 ± 0.02N per side with 95% CI [-0.03, 0.01], which was also significantly less than the protraction forces exerted during dental-anchored retraction ($p < 0.001$) (Fig 3.13).

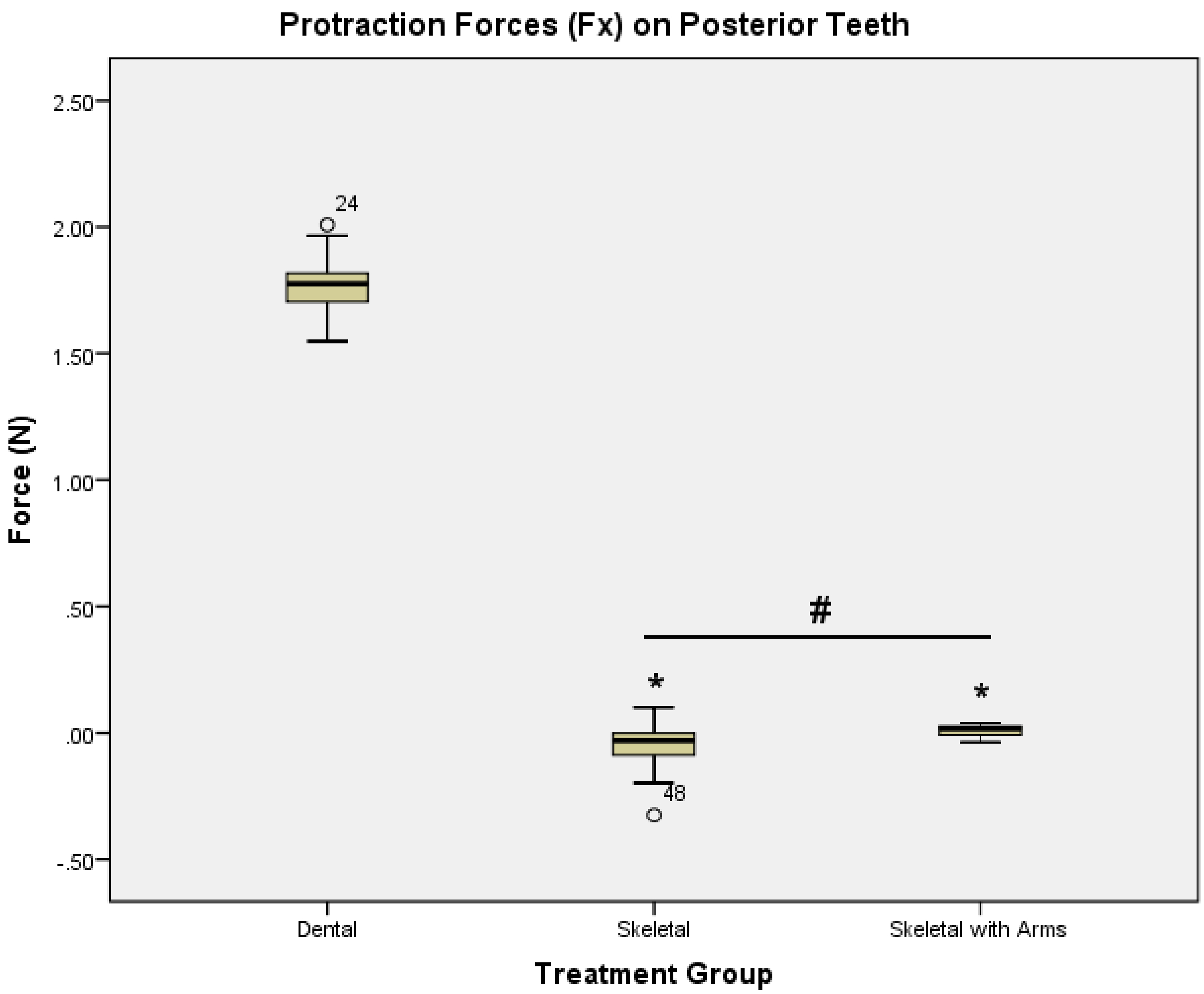

Figure 3.13. Comparison of protraction forces on the posterior teeth segment. (*) denotes difference to 'Dental' group ($p < 0.001$). (#) $p < 0.001$.

3.3.6 Buccal-palatal forces on the posterior teeth

Inward palatal forces acting on the posterior anchor segment contribute to palatal movement of this segment and a decrease in dental arch width. The force vector produced by the retraction springs generates an inward component force vector since the anterior insertion point of the spring is more palatal than the posterior insertion point.

Traditional dental-anchorage generated the largest inward forces of 0.60 ± 0.07N per side with 95% CI [0.59, 0.62]. Skeletal anchorage removed the retraction spring from directly acting on the posterior anchorage segment and significantly reduced the inward component force to virtually zero 0.00 ± 0.05N per side with 95% CI [-0.02, 0.01] ($p < 0.001$). The addition of archwire power arms to skeletal-anchorage retraction maintained virtually zero inward forces on the first molars -0.02 ± 0.02N per side with 95% CI [-0.04, 0.00]. This value was also significantly less than the inward forces exerted during dental-anchored retraction ($p < 0.001$) (Fig 3.14).

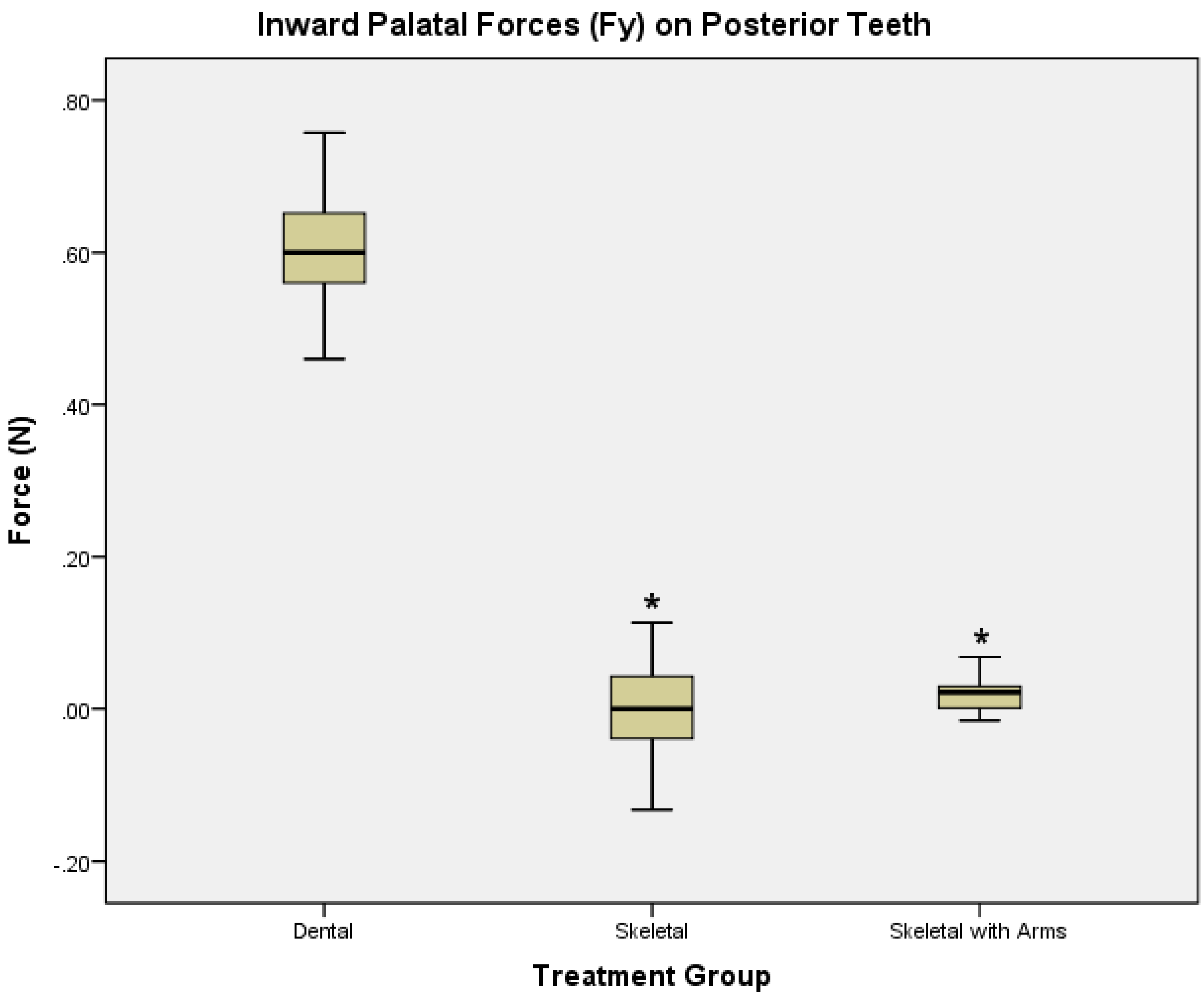

Figure 3.14. Inward palatal forces acting on the posterior teeth segment. (*) denotes difference to 'Dental' group (p < 0.001).

3.3.7 Vertical forces on the posterior teeth

Vertical forces acting on the posterior anchor segment will introduce potential vertical movements in those teeth. Upward forces may cause intrusion of the segment, while downward forces may cause extrusion of the segment. Force measurements from the load cells attributed positive values as upward intrusive forces and negative values as downward extrusive forces.

Traditional dental-anchorage generated minimal downward extrusive forces on the posterior anchor segment of -0.01 ± 0.05N per side with 95% CI [-0.02, 0.01]. Skeletal anchorage increased the downward extrusive force to -0.06 ± 0.04N per side with 95% CI [-0.08, -0.05] ($p < 0.001$). The addition of archwire power arms to skeletal-anchorage retraction reduced the vertical forces acting on the posterior segment to -0.02 ± 0.02N per side with 95% CI [-0.04, 0.00] ($p < 0.001$) (Fig 3.15).

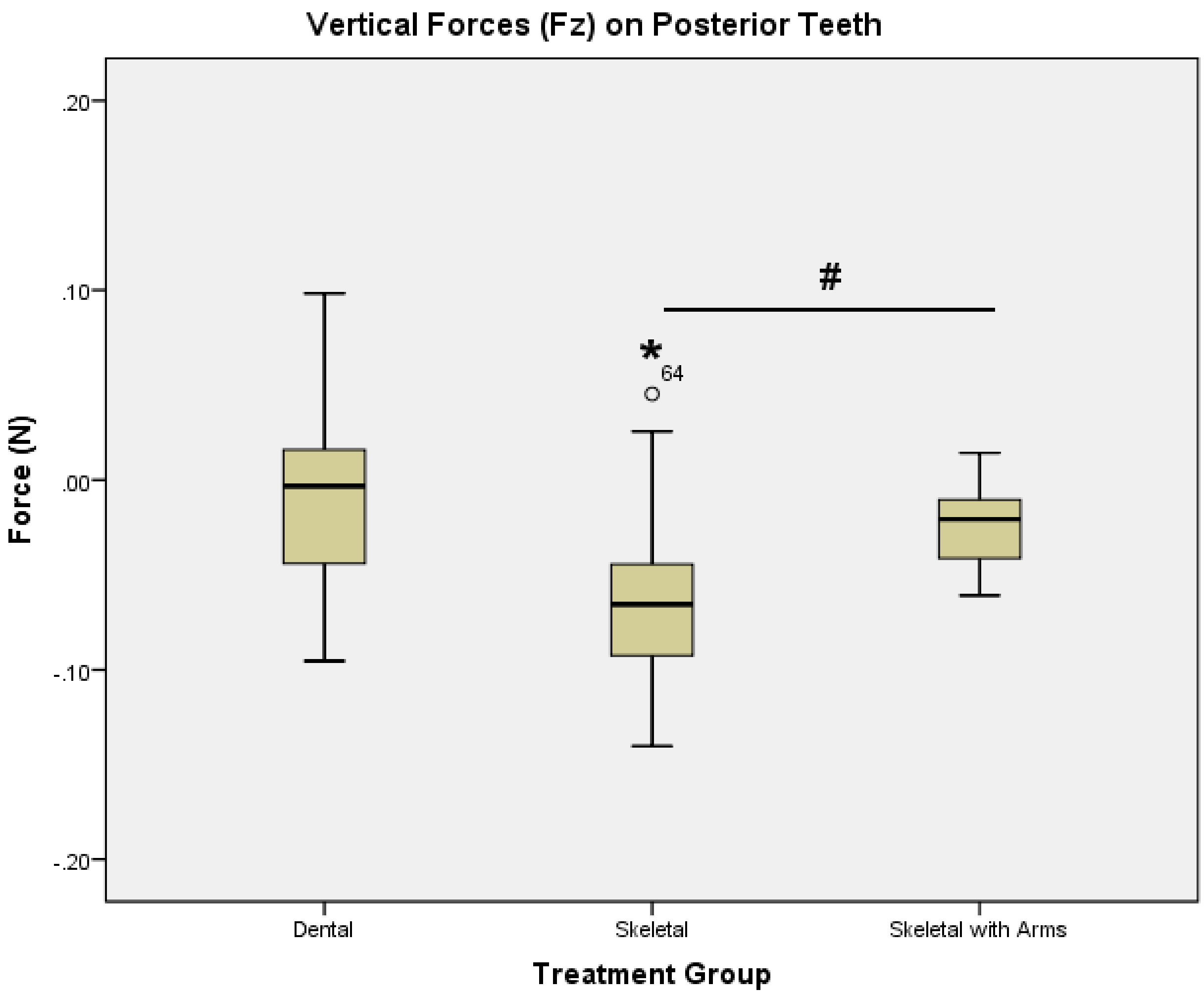

Figure 3.15. Comparison of vertical forces acting on the posterior teeth segment. (*) denotes difference to 'Dental' group ($p < 0.001$). (#) $p < 0.001$.

3.3.8 Vertical force propagation in the dental arch

To investigate how the forces from the retraction springs propagated throughout the dental arch, force profile plots were generated to compare the three treatment groups. In all three groups the greatest upward vertical forces were exerted on the lateral incisor teeth (1.2 & 2.2).

This finding is consistent with the point of force application being nearest to the lateral incisors. The greatest vertical force occurred in the skeletal-anchored group with power arms. A reciprocal downward force was measured in the canines (1.3 & 2.3) in group 3 due to the moment generated by the power arms onto the AW. The downward force measured in the canines was either absent or significantly less in groups 1 and 2. Finally, in general the vertical forces dissipate towards the posterior end of the dental arch (Fig 3.16).

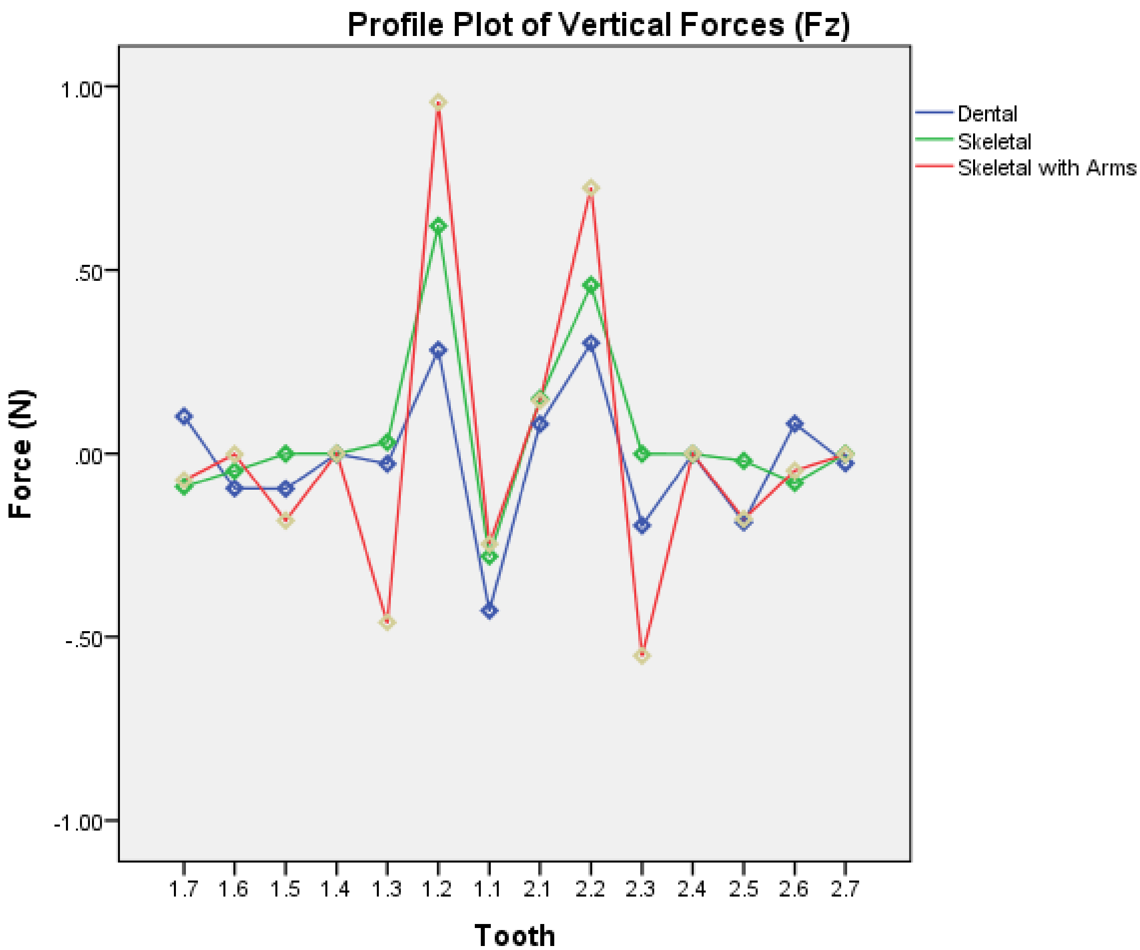

Figure 3.16. Vertical forces acting on each tooth in the maxillary dental arch between treatment groups.

3.4 Discussion

This study evaluated the initial forces in three dimensions exhibited on the anterior and posterior dentition during en-masse retraction space closure. Three treatment modalities were compared including conventional dentally-anchored, conventional skeletally-anchored, and skeletally-anchored with archwire power arms.

3.4.1 Maximal forces exhibited on laterals 1.2 and 2.2

In all three treatment groups, the retraction spring was connected to the archwire via an archwire post or an extension arm situated between the lateral incisors and canines. As a result, none of the anterior teeth were directly engaged by the retraction spring. All forces acting on the anterior teeth were resultant from forces transmitted by the archwire. Although the retraction springs were not directly engaged on any of the anterior teeth, the lateral incisors (1.2 and 2.2) experienced the greatest forces, both horizontal and vertical (Fig 3.17). This was due to the proximity of those teeth to the archwire post or extension arm where the force was applied. While also close to the point of force application, the canines experienced less forces than the lateral incisors. Horizontal retraction forces acting on the canines were less because of the orientation of the canine bracket. Whereas the lateral bracket is positioned somewhat perpendicular to the retraction force, the canine bracket is positioned more parallel. The component forces acting on the bracket bases and hence the teeth decrease as the brackets arrange more parallel to the applied force vector. Hence the horizontal retraction forces experienced by the canines were less than the laterals. Vertical forces acting on the laterals were the highest, particularly when skeletal-anchorage was used. By applying the retraction spring forces on the archwire posts or power arms, the force vector did not pass through the center of the archwire resulting in a moment. The anterior portion of the archwire experienced an upward rotation while the posterior portion of the archwire experienced a downward rotation (Fig 3.18). The moment in the archwire increased the upward vertical forces experienced by the lateral incisors more than the canine leading to the greatest vertical forces recorded at the laterals.

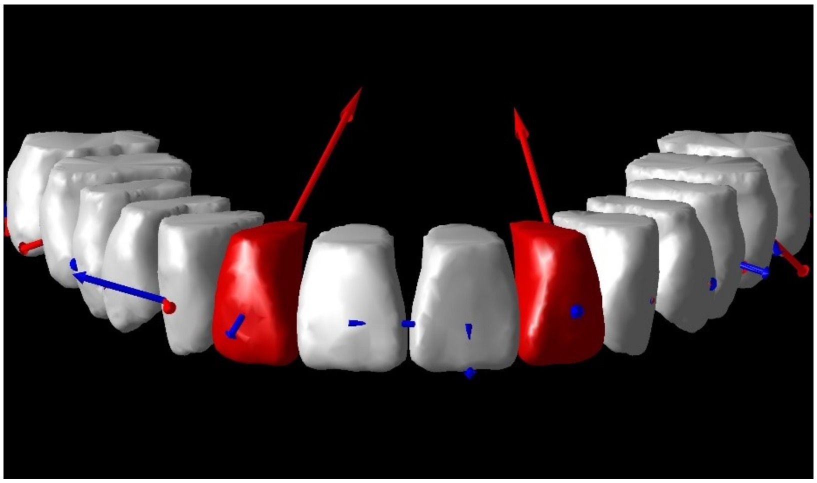

Figure 3.17. Maximal forces acting on lateral incisors.

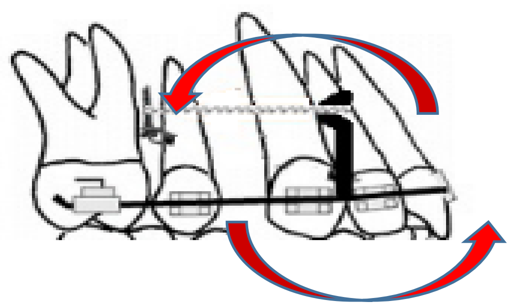

Figure 3.18. Power arms create localized moment in archwire.

3.4.2 Power arms create a localized moment in archwire.

The management of moments during tooth movement is of importance to the clinician to minimize unwanted movements. Whereas the center of resistance of teeth typically resides somewhere along the root length, forces are often applied at the level of the tooth crown, leading to the generation of moments. During space closure these moments lead to tipping of teeth into the extraction space. Tipping is often unwanted thus creating the need to upright the roots once the spaces are closed. One strategy employed by clinicians to avoid unwanted moments is to utilize power arms to better approximate force application at the center of resistance of teeth. This strategy reduces the magnitude of generated moments, leading to greater bodily movement and less tipping of teeth. For en-masse space closure, power arms are sometimes added to approximate the center of resistance of the entire anterior retraction unit in hopes of mitigating the vertical forces introduced with skeletal-anchored retraction. In this study, power arms were added to examine how their addition affected the vertical and horizontal forces experienced by the anterior and posterior teeth. Vertical forces acting on the entire anterior retraction unit were reduced when power arms were used when compared with conventional skeletal-anchorage, supporting their use in situations where reduced vertical forces are desirable. However, when examined further the upward vertical forces acting on the laterals was actually increased when compared with conventional skeletal-anchorage. Furthermore, the canines experience a downward vertical force which was not present in the other groups (Fig 3.19). The explanation for these findings is that the power arm acts as a moment arm and flexes the archwire where the power arm attaches to the archwire. These findings suggest that in cases where canine extrusion is unfavourable that power arms should be used with caution (or may not be used) to avoid excessive extrusive forces.

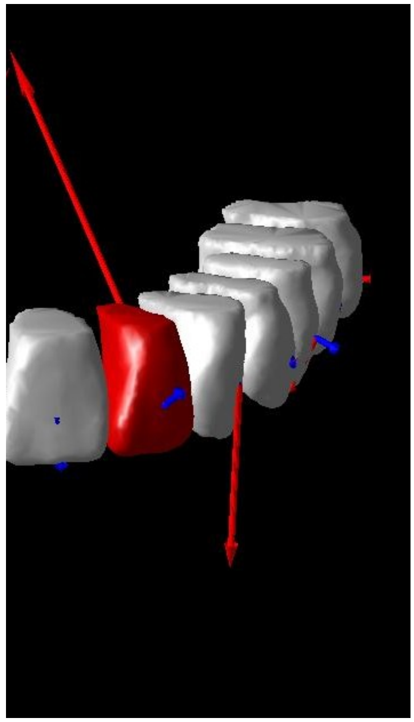

Figure 3.19. Power arms generate extrusive forces on canines.

3.4.3 Forces exerted by archwire decay rapidly from source of application

Both horizontal and vertical forces were maximal near the archwire posts and their adjacent brackets, which then quickly decayed along the archwire. Central incisor forces were lower than lateral incisor forces in both the horizontal and vertical directions suggesting that the lateral incisor brackets absorbed a large portion of the archwire forces reducing their transmission to the central incisors (Fig 3.20). Similarly, although vertical forces were generated in the skeletally anchored groups, they were detected primarily in the anterior segment and minimal vertical forces were detected in the posterior anchor segment. This again suggests that the initial archwire forces are primarily acting on the teeth adjacent to the archwire posts, which drastically reduces the transmission of those forces along the archwire.

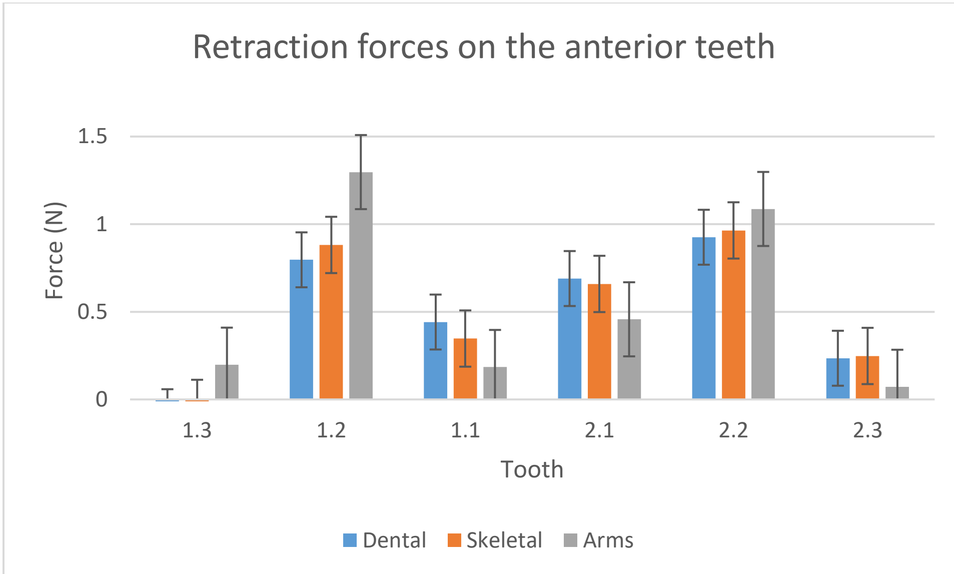

Figure 3.20. Retraction forces experienced by central incisors is reduced by the high forces absorbed by the lateral incisors.

3.4.4 Asymmetrical load measurements

Comparison of loads between mirrored teeth (e.g. tooth 1.2 versus tooth 2.2) in the dental arch showed variations between the left and right sides. Although the general trend was conserved between left and right sides, minor variations in load measurements were recorded. This suggests that there were subtle differences in the arch between the left and right sides during experimentation. A possible explanation for this would include minor shifting of the archwire towards one side or the other during activation or deactivation of the retraction springs. Additionally, flexing of the archwire during force application could potentially distort it and produce the asymmetrical load measurements. Since a purely symmetrical malocclusion is a clinical rarity, absolute force symmetry during orthodontic space closure is generally not a primary goal. Consequently, the overall trend affecting the anterior and posterior units is more valuable to clinicians.

3.4.5 Clinical significance

Precise control of forces applied to teeth during retraction is important to the clinician to manage which teeth move and by how much. Forces in the range of 0.35-0.60N have been reported to produce dental tipping and extrusion, whereas slightly greater forces in the range of 0.70-1.20N have been reported to produce bodily movement.[2] In the present study, all retraction groups generated sufficient force to retract the anterior teeth by producing approximately 0.5N per tooth, which implies mainly tipping forces. Compared with dental anchorage, skeletal anchorage increased the retraction force per tooth by 0.05N to approximately 0.55N. While this increase was found to be statistically significant, whether there would be any noticeable differences in retraction rate or treatment time is unknown.

In cases where minimal forward movement of anchor teeth is favourable, then minimizing forces as close to zero is desirable. Treatments that require maximum anchorage, such as treating severe dental protrusion, fall under this category and achieving good clinical results hinges on preventing unwanted anchorage loss. Skeletal-anchorage, both with or without power arms, significantly reduced the protractive forces on the anchor teeth when compared to traditional dental-anchorage. By connecting the retraction springs to the fixed skeletal anchorage instead of directly onto the upper molars, forces in all three dimensions were reduced. Additionally, forces exerted by the archwire on the posterior unit were minimal.

The use of skeletal anchorage increased the vertical forces on the anterior teeth segment when compared with dental anchorage. In cases where intrusion of the anterior teeth is desirable then these additional vertical forces would be favourable. One such case would be a deep bite malocclusion caused by over-eruption of the maxillary anterior teeth. The additional vertical component of force provided by skeletal anchorage would simultaneously help correct the deep bite during the space closure phase, saving both the clinician and patient valuable treatment time.

However, the vertical forces afforded by skeletal anchorage could be detrimental to shallow bite malocclusion where intrusion of anterior teeth is unfavourable. When treating a shallow bite malocclusion, the clinician will have to manage the intrusive effects of skeletal anchorage by either subsequently extruding the anterior teeth in a post space closure phase, or opting for dental anchorage instead. Careful consideration of pros and cons will have to be made on a case by case basis to determine the best retraction method in shallow bite malocclusion cases.

The addition of power arms during skeletal anchored en-masse retraction provides the benefits of maximum anchorage afforded by skeletal anchorage while reducing its vertical forces. This may improve treatment outcomes as well as decrease treatment times when used to treat cases where intrusion of anterior teeth is unfavourable but maximum anchorage is required. However, the power arms apply extrusive forces to the canines that may create occlusal interferences that inhibit space closure or prevent occlusal settling. Both of these side-effects could increase treatment times and decrease treatment outcomes. Therefore, careful case selection and treatment management is important to the clinician when utilizing power arms during skeletal anchored retraction.

3.4.6 Study limitations

This study only evaluated the initial forces experienced by the dental arch immediately after engaging the retraction springs. As such, the results reflect the initial static forces in three-dimensions of each tooth before any tooth movement has occurred. During en-masse space closure, the teeth in the anterior and posterior segments will undergo some combination of tipping and bodily movement, which will alter the forces acting on those teeth. It is expected that both vertical and horizontal forces will vary during this space closure phase as the forces applied by the archwire onto the bracket and hence tooth will change vector over time. Focus was on the initial forces only as this setup was the most readily reproducible and controllable.

3.5 Conclusion

All methods produced sufficient forces to retract the anterior teeth during en-masse retraction. Skeletal-anchorage reduced forces on the posterior teeth and introduced greater vertical forces on the anterior teeth. The addition of power arms during skeletal-anchorage reduced vertical forces on the anterior teeth but created a localized moment in the archwire generating canine extrusive forces and increased lateral incisor intrusive forces.

4 General Discussion

4.1 Final Discussion

How forces influence tooth movement continues to be an important area of study for orthodontists. From managing anchorage to the prevention of unwanted tooth movements, clinicians constantly employ biomechanical principles during treatment. Clinical techniques to simplify the force system improve the predictability of tooth movement. However, much of orthodontic treatment continues to utilize force systems with high complexity, such as en-masse retraction with continuous archwire mechanics. As has been shown in this study, forces propagate from their points of application and can potentially influence teeth at distant sites. Therefore, it is important to both plan for and manage those forces to achieve greater tooth movement predictability.

Under clinical situations where minimal posterior anchorage loss is desirable, skeletal anchorage is indicated. Both skeletal anchorage groups showed significant reductions to forces placed on the posterior anchorage unit. However, forces were not completely eliminated. Force propagation via the archwire likely explains this finding. Vertical forces may still act on the posterior teeth and possibly lead to some extrusion. This increase in extrusive forces was possibly due to the increased upward forces exerted on the anterior archwire during skeletal-anchored retraction creating a reciprocal downward rotation of the posterior archwire.

This experiment sought to recreate the dental arch as accurately as possible using the OSIM device. The complete dental arch, excluding the third molars and the first premolars were measured and a temperature controlled chamber reproduced oral conditions. However, the influence of the periodontal ligament and supporting periodontium was not included nor measured in this experiment. Compliance of the periodontal ligament and supporting periodontium during orthodontic tooth movement provides a cushioning effect on the dental root from applied forces. Conceptually, they provide a shock absorber effect to the dentition when a force is applied. However, this effect occurs over the course of a few seconds after which will reach an equilibrium.[1] Since this experiment investigated the equilibrium state rather than dynamic forces, the influence of periodontal ligament compliance theoretically should be negligible.

4.2 Recommendations

This study provided force measurements during the initial moments of en-masse retraction space closure. Future investigation can measure the forces that occur at other stages of space closure, such as mid-closure or after the spaces of been closed.

Since space closure is a dynamic process, dynamic measurements while the space is closing would be interesting. However, accurate reproduction of the events that occur during space closure would be difficult. Space closure requires many weeks and clinical appointments, introducing a lot of variability. Also, the effects of friction, binding, and perturbations play a role in sliding mechanics that can be challenging to reproduce experimentally.

The OSIM represented the individual teeth using rectangular pegs that did not directly contact each other. This increased the ability to measure the forces exerted on each tooth but prevents the contribution of tooth-to-tooth contact and force propagation from occurring. Recreating anatomically correct teeth that are in contact would highlight the effect of force transmission between tooth contacts.

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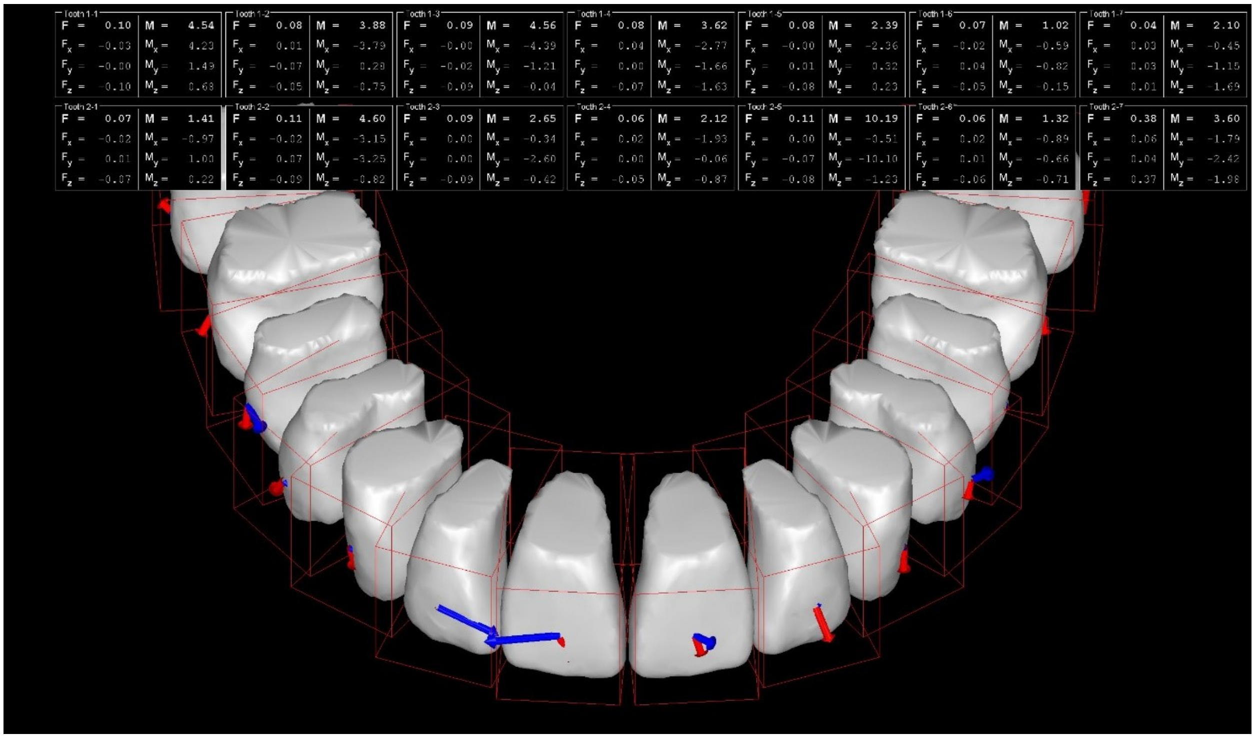
Appendix

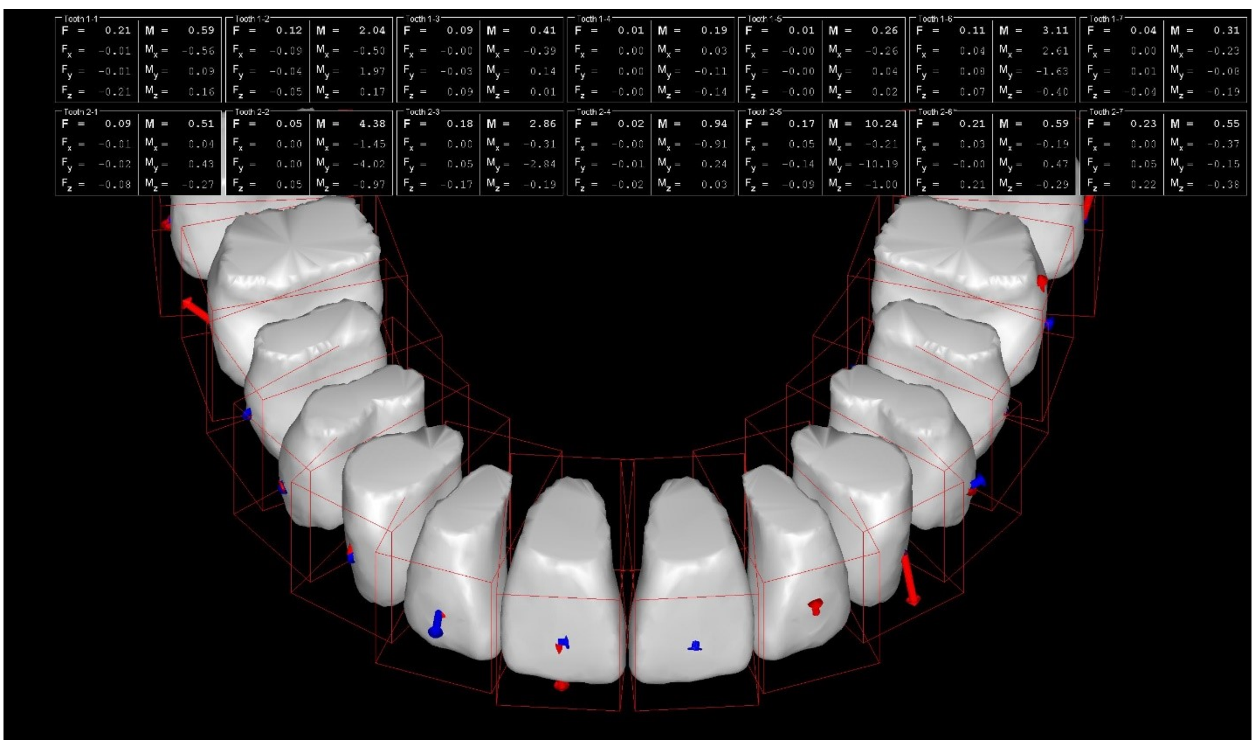
Appendix A: Sensitivity Study

During the main study, small residual forces were observed in the OSIM system between activations of the retraction springs. This observation was possibly due to slight shifting of the archwire that occurs when the retraction springs are activated or deactivated. Since the load cells were zeroed prior to each test run, we wanted to investigate the impact of these residual forces on the load cell measurements. Testing was carried out identical to the main study, except only the dental-anchorage configuration was used. Two test groups were created, each with N=10:

1) Control group: Standard pre-test setup where forces measured on each load cell prior to testing were 0.10N or less.
2) Offset group: Pre-test setup where forces measured prior to testing were 0.20N or less.

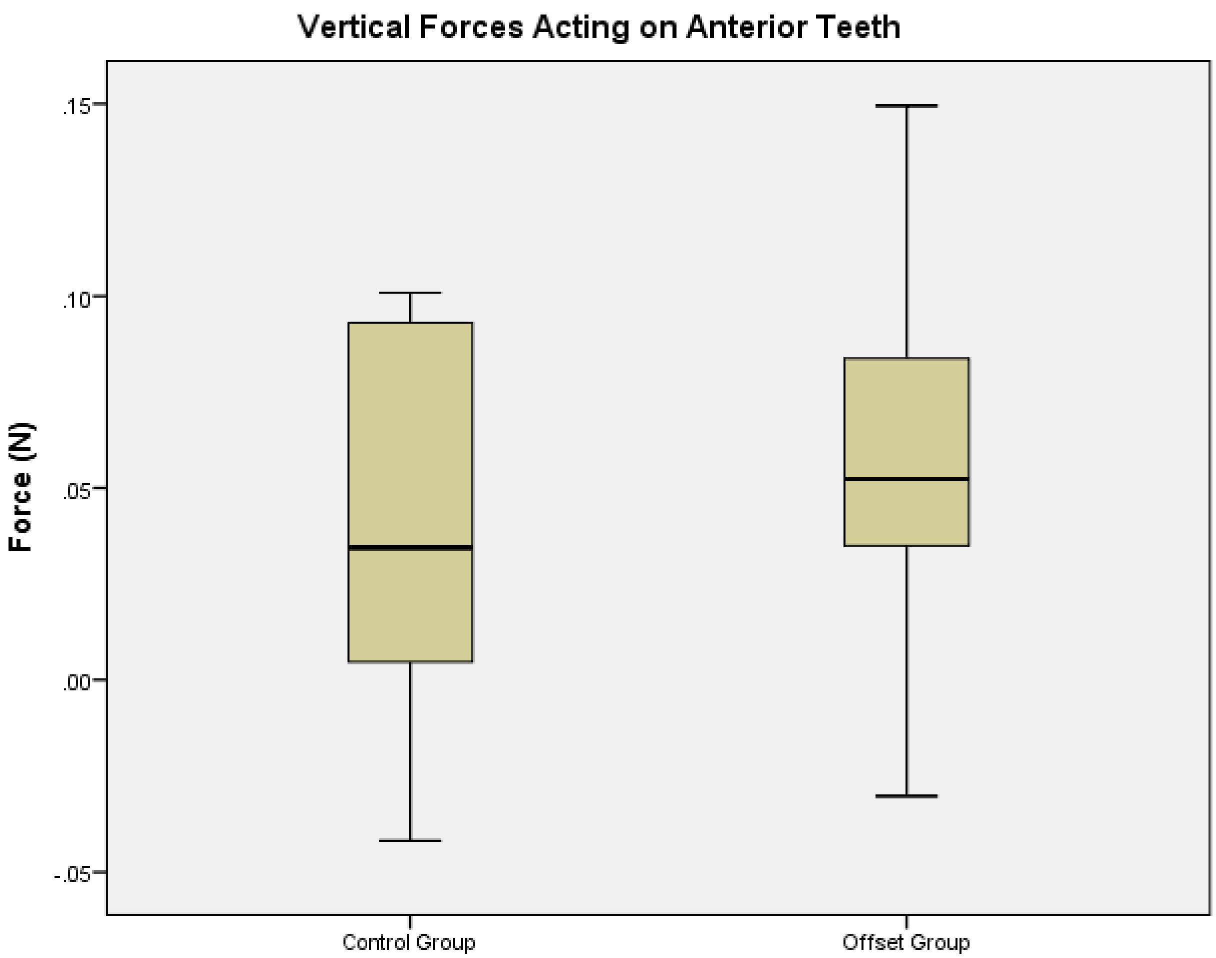


Control Group pre-test setup. Load cells kept to 0.10N or less.

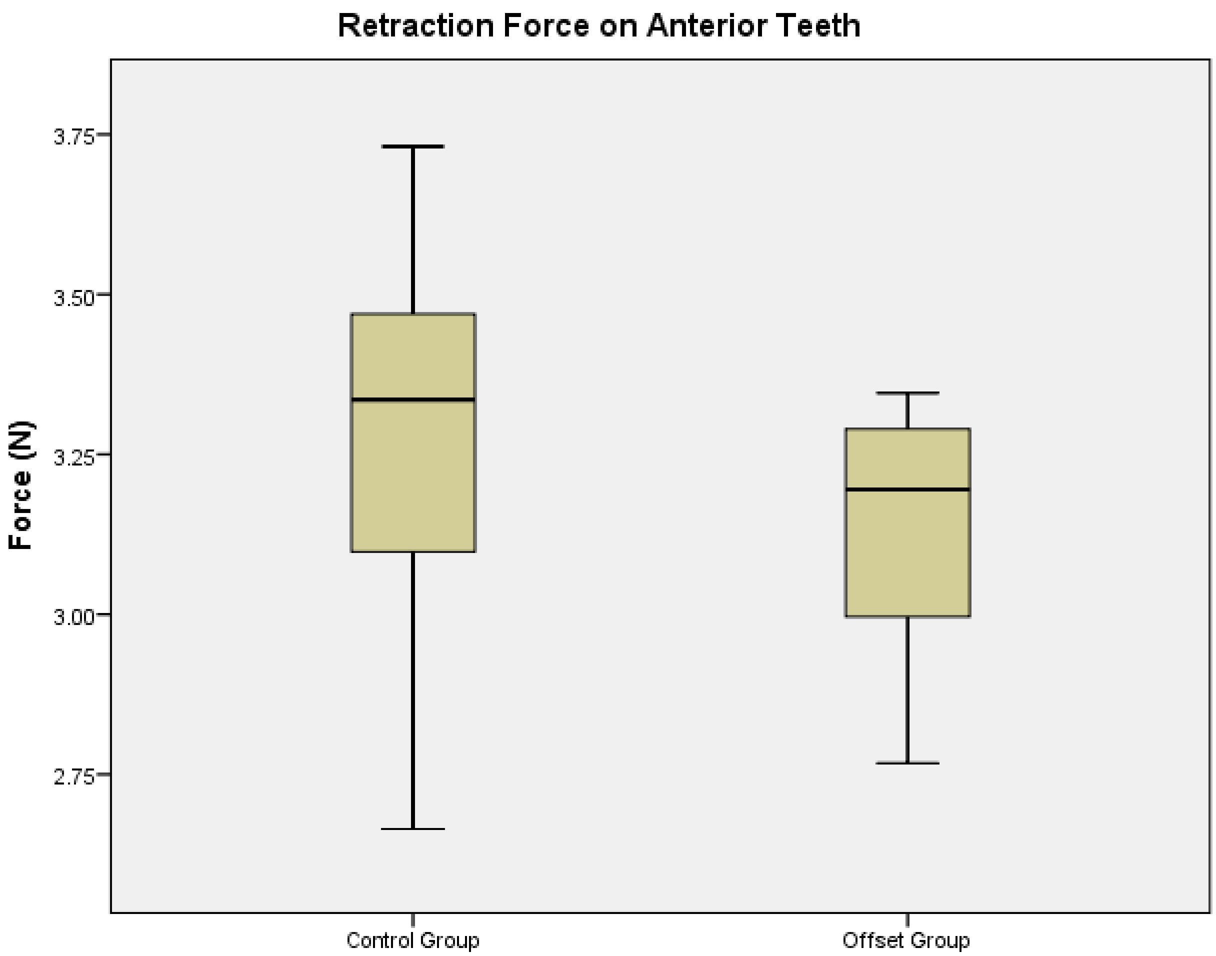


Offset Group pre-test setup. Load cell measurements were 0.20N or less.

Two outcome measures were compared between the testing groups: 1) Vertical forces (FzSUM) on the anterior teeth segment, 2) Retraction forces (F_dSUM) on the anterior teeth segment. Vertical forces (FzSUM) were 0.04 ± 0.05N with 95% CI [0.01, 0.07] in the control group and 0.06 ± 0.05N with 95% CI [0.03, 0.09] in the offset group. No difference in the means (p = 0.447) or variances were detected. Retraction forces (F_dSUM) were 3.26 ± 0.33N with 95% CI [3.02, 3.50] in the control group and 3.13 ± 0.21N with 95% CI [3.00, 3.28] in the offset group. No difference in the means (p = 0.307) or variances were detected.



Vertical forces acting on the anterior teeth segment. No difference between the control and offset groups.



Retraction forces on the anterior teeth segment. No difference between the control and offset groups.

Results from the sensitivity study found no significant differences between the control and offset groups. This finding suggests that small residual forces in the OSIM force system between test runs do not significantly alter the load cell measurements during testing. Consequently, we do not expect that zeroing the load cells prior to each test run influenced the differences detected in the main study.

Appendix B: Force Data Tables

Anterior teeth segment – Retraction Force

Anterior teeth segment Retraction Force – Descriptives.

Treatment Group	Mean (N)	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Dental	2.990	.039	2.914	3.067
Skeletal	3.052	.039	2.976	3.128
Skeletal with Arms	3.297	.039	3.221	3.374

Anterior teeth segment Retraction Force - Pairwise Comparison.

Treatment Group	Treatment Group	Mean Difference (N) (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Dental	Skeletal	-.062	.048	.488	-.179	.055
	Skeletal with Arms	-.307	.063	.000	-.461	-.153
Skeletal	Dental	.062	.048	.488	-.055	.179
	Skeletal with Arms	-.245	.052	.000	-.373	-.118
Skeletal with Arms	Dental	.307	.063	.000	.153	.461
	Skeletal	.245	.052	.000	.118	.373

Anterior teeth segment – Vertical Force

Anterior teeth segment Vertical Force – Descriptives.

Treatment Group	Mean (N)	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Dental	.012	.014	-.015	.038
Skeletal	.978	.014	.952	1.005
Skeletal with Arms	.568	.014	.541	.595

Anterior teeth segment Vertical Force – Pairwise Comparison.

Treatment Group	Treatment Group	Mean Difference (N) (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Dental	Skeletal	-.967	.015	.000	-1.00	-.930
	Skeletal with Arms	-.556	.021	.000	-.608	-.505
Skeletal	Dental	.967	.015	.000	.930	1.00
	Skeletal with Arms	.410	.021	.000	.359	.462
Skeletal with Arms	Dental	.556	.021	.000	.505	.608
	Skeletal	-.410	.021	.000	-.462	-.359

Posterior teeth segment – Protraction Force

Posterior teeth segment Protraction Force – Descriptives.

Treatment Group	Mean (N)	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Dental	-1.771	.012	-1.794	-1.748
Skeletal	.050	.012	.027	.073
Skeletal with Arms	-.010	.012	-.033	.013

Posterior teeth segment Protraction Force – Pairwise Comparison.

Treatment Group	Treatment Group	Mean Difference (N) (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Dental	Skeletal	-1.822	.020	.000	-1.870	-1.773
	Skeletal with Arms	-1.762	.016	.000	-1.801	-1.722
Skeletal	Dental	1.822	.020	.000	1.773	1.870
	Skeletal with Arms	.060	.013	.000	.028	.092
Skeletal with Arms	Dental	1.762	.016	.000	1.722	1.801
	Skeletal	-.060	.013	.000	-.092	-.028

Posterior teeth segment – Buccal-Palatal Force

Posterior teeth segment Buccal-Palatal Force – Descriptives.

Treatment Group	Mean (N)	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Dental	-.602	.008	-.618	-.586
Skeletal	-.003	.008	-.018	.013
Skeletal with Arms	-.020	.008	-.036	-.004

Posterior teeth segment Buccal-Palatal Force – Pairwise Comparison.

Treatment Group	Treatment Group	Mean Difference (N) (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Dental	Skeletal	-.600	.013	.000	-.632	-.567
	Skeletal with Arms	-.582	.011	.000	-.610	-.555
Skeletal	Dental	.600	.013	.000	.567	.632
	Skeletal with Arms	.017	.009	.166	-.005	.040
Skeletal with Arms	Dental	.582	.011	.000	.555	.610
	Skeletal	-.017	.009	.166	-.040	.005

Posterior teeth segment – Vertical Force

Posterior teeth segment Vertical Force – Descriptives.

Treatmeng Group	Mean (N)	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Dental	-.007	.006	-.018	.005
Skeletal	-.064	.006	-.076	-.053
Skeletal with Arms	-.024	.006	-.036	-.012

Posterior teeth segment Vertical Force – Pairwise Comparison.

Treatment Group	Treatment Group	Mean Difference (N) (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Dental	Skeletal	.058	.010	.000	.034	.081
	Skeletal with Arms	.017	.008	.110	-.003	.037
Skeletal	Dental	-.058	.010	.000	-.081	-.034
	Skeletal with Arms	-.040	.007	.000	-.057	-.023
Skeletal with Arms	Dental	-.017	.008	.110	-.037	.003
	Skeletal	.040	.007	.000	.023	.057