Orthodontic Simulation of Forces and Moments Using Space Generation Mechanics with a Lingual Bracket System

by

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Abstract

Objectives: Evaluation of the three dimensional (3D) forces and moments exerted by lingual orthodontic brackets in a simulated dental arch with crowded teeth. Statistical and mechanical analysis of the forces and moments between two different treatment mechanics (NiTi coil springs and archwire stops) and two different archwire systems (straight and mushroom) were used to understand which systems may produce the most physiologic forces and moments.

Methods: Data was collected using an Orthodontic Simulator (OSIM); an in-vitro model of the human mouth to measure 3D forces and moments on each tooth in the dental arch. Lingual braces were positioned on anatomically designed metal teeth on the OSIM. The metal teeth simulations were attached to load cells which measured the 3D forces and moments experienced by all of the teeth in the dental arch simultaneously. Teeth in the anterior dental arch were moved from a crowded position to the desired neutral uncrowded position to simulate space generation for a crowded dentition. Four experimental groups were examined: 1. NiTi coil springs with straight archwires, 2. NiTi coil springs with mushroom archwires, 3. Archwire stops with straight archwires, 4. Archwire stops with mushroom archwires. Statistical analysis was utilized to determine differences in treatment mechanics between the groups.

Results: Three overall observations were noticed during our analysis: 1. Mushroom archwires had similar mean force and moment values despite which treatment type was used, 2. Coils treatment mechanics had similar mean force and moment values despite which archwire type was used, 3. Both archwire types had greater mean force and moment values when using stops compared to coils.

Conclusions: There were differences in the mean forces and moments of interest (F_x, F_y, M_x, M_y, M_z) experienced by the teeth of interest (maxillary first premolars and maxillary lateral incisors) between the two different treatments (coils and stops) and the two different archwires (straight archwires and mushroom archwires) at the maximum crowded position. Many of the forces and moments measured were above the threshold for clinically significant tooth movement.

Table of Contents

Table of Contents iv

Chapter 1 Introduction 1
- 1.1 Introduction 1
- 1.2 Study Design 6
- 1.3 Research Questions 7
- 1.4 Research Objectives 7

Chapter 2 Literature Review 12
- 2.1 Introduction 12
- 2.2 Biology of Tooth Movement 13
- 2.3 Biomechanics of Tooth Movement 14
- 2.4 Lingual Orthodontic Treatment 18
- 2.5 Lingual Braces Compared to Labial Braces 22
- 2.6 In Vitro Methods for Studying Orthodontic Biomechanics 23
- 2.7 Orthodontic Simulator (OSIM) 25
- 2.8 Space Generation Treatment Mechanics 26
- 2.9 Lingual Archwires 27
- 2.10 Clinically Significant Tooth Movement 28

Chapter 3 In Vitro Simulation of Forces and Moments Using Space Generation Mechanics with a Lingual Bracket System 37
- 3.1 Introduction 37
- 3.2 Materials and Methods 39
  - 3.2.1 Orthodontic Simulator (OSIM) 39
  - 3.2.2 Orthodontic Materials 41
  - 3.2.3 Experimental Set-up 41
  - 3.2.4 Force and Moment Measurements 45
  - 3.2.5 Sample Size Calculation 46
  - 3.2.6 Statistical Analysis 46
- 3.3 Hypotheses 48
- 3.4 Results 49
  - 3.4.1 Comparison of Average Force and Moments 49
  - 3.4.2 Anterior Force Comparisons 52
  - 3.4.3 Comparing Treatment Mechanics 54
  - 3.4.4 Comparing Wire Types 55
- 3.5 Discussion 57
  - 3.5.1 Discussion of overall trends 57
  - 3.5.3 Straight Archwire Stops Data 61
  - 3.5.4 Clinical Significance 62
- 3.6 Conclusion 63

Chapter 4 Final Discussion 67
- 4.1 General Discussion 67

4.2 Study Limitations 68
4.3 Future Recommendations 69
Appendix 81
1.1 Interaction between Wire Type and Treatment Type 81
2.1 Straight Archwire Stops Data 84

List of Figures

Figure 1.1 Mechanics used for generating space in a dental arch 4

Figure 1.2 Shapes of archwires used for lingual brackets...5

Figure 2.1 Difference between Center of Resistance and Center of Rotation on a tooth 15

Figure 2.2 Arch forms with labial and lingual brackets...17

Figure 2.3 Bracket location and Center of Resistance 18

Figure 3.1 Orthodontic Simulator (OSIM)...39

Figure 3.2 Computer display of OSIM experiment 40

Figure 3.3 Illustrations of a maxillary dentition with and without crowded teeth.......................42

Figure 3.4 Experimental set-up positions on the OSIM..43

Figure 3.5 Representative coordinate system for a single simulated tooth on OSIM..................45

Figure 3.6 Average forces between the experimental groups 50

Figure 3.7 Average moments between the experimental groups..51

Figure 3.8 Sum of the total anterior force of the four anterior teeth...52

Figure 3.9 Calculation of Fa values 53

Figure 3.10 Average total anterior force between groups 53

List of Tables

Table 3.1 Univariate Pairwise Comparisons at the Maximum Crowded Position of First Premolars and Lateral Incisors for Wire Type when using Different Treatments................54

Table 3.2 Univariate Pairwise Comparisons at the Maximum Crowded Position of First Premolars and Lateral Incisors for Treatment Type when using Different Archwires.........56

List of Acronyms:

OSIM: Orthodontic Simulator

NiTi: Nickel Titanium

PDL: Periodontal Ligament

Chapter 1 Introduction

1.1 Introduction

Orthodontics is an area of dentistry that specializes in diagnosing and treating malocclusions of dental, skeletal, functional, and multifactorial etiologies. Orthodontic treatment involves applying forces to the teeth, which causes the teeth to move as a result of bone remodeling[1]. Teeth that are crooked, crowded, or otherwise misaligned may cause decreased self-esteem[2], and may impair masticatory function[3]. Crowded or misaligned teeth may also cause patients to have more difficulty maintaining adequate oral hygiene, which may lead to gingival problems or periodontal disease[4]. The goal of orthodontic treatment is to align the teeth in a functional and physiologic position. Therefore, orthodontic treatment can benefit patients functionally[3], esthetically[2], psychosocially[2], and has the potential to lead to improved oral health[4].

It is important to understand the biomechanics of orthodontic treatment to provide patients with the most efficient treatment plan. Inappropriate application of orthodontic forces to the teeth could potentially result in increased damage to the teeth and surrounding structures[1], increased treatment time, or increased pain during treatment[5]. Extended treatment times can potentially lead to root resorption[6], white spot decalcifications[6], or caries[6].

Lingual orthodontic fixed appliance treatment (lingual braces) may provide the patient with certain social and esthetic advantages over traditional labial orthodontic treatment[7]. An advantage of lingual orthodontic treatment is that the appliances are less visible as they reside on the inside surfaces of the teeth[8]. With many adult patients currently seeking orthodontic treatment, lingual orthodontic treatment may provide an esthetic treatment option that many adult patients are looking for[9 10].

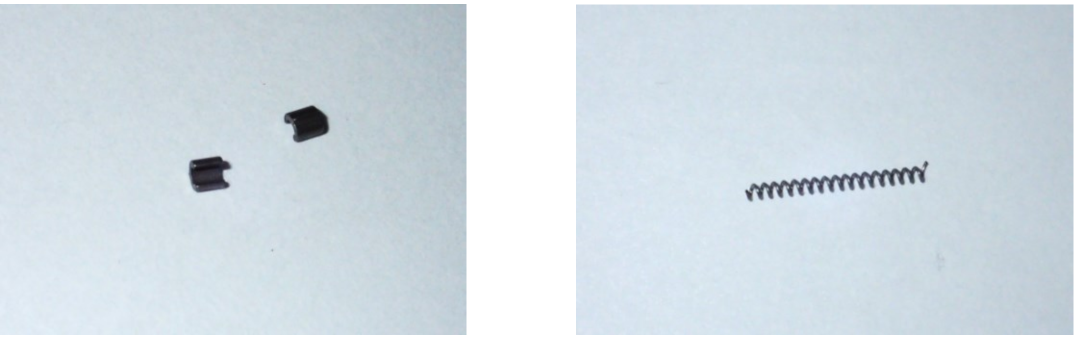
Lingual orthodontic treatment has different biomechanical considerations compared to traditional labial orthodontic systems. Applying orthodontic forces from the lingual surfaces of the teeth must be considered differently than applying forces to the labial surfaces[11]. The difference in location of orthodontic force application causes a different pattern of load transfer to the underlying roots, periodontal ligament, and alveolar bone. The load transfer of the orthodontic force to the underlying biologic structures is what causes the tooth to move through the alveolar bone. The differences in biomechanics when using lingual braces must be taken into consideration to provide treatment that allows the teeth to move to the desired locations without causing damage to the surrounding biologic structures. Currently, there is minimal literature available with regard to the biomechanics of lingual orthodontic treatment.

Understanding the orthodontic biomechanical differences between labial and lingual systems begins with recognizing the various fundamental differences between the two systems. A distinct difference between lingual orthodontic treatment compared to labial treatment is the size and shape of the dental arch. The lingual surfaces of the teeth have a more constricted arch size compared to the labial surfaces[12]. The anatomy of the lingual surfaces of the teeth also create a different arch form shape compared to the labial surfaces[12]. The labial arch form has a continuous parabolic shape, compared to the lingual arch form that has a step between the canines and first premolars[12]. The anatomy of the lingual surfaces of the anterior teeth are concave in shape, compared to the convex shape of the labial surfaces[13]. This difference in anatomy affects the relationship between the bracket and tooth surface. The specific position that the bracket is placed on the tooth also affects the relationship between the applied orthodontic forces to the center of resistance of the tooth[12]. Differences between the distance of force application and the center of resistance of the tooth will affect the resultant forces and moments that will be experienced by the tooth[12]. The distance between the brackets (inter-bracket distance) is larger with labial compared to lingual brackets[14 15]. This decrease in inter-bracket distance with lingual brackets affects the amount of wire between adjacent brackets, and therefore affects the mechanical properties of the wire[14 15]. All of these differences between labial and lingual brackets create complex biomechanical systems that must be understood to ensure efficient orthodontic treatment results.

Measuring the forces and moments experienced by the teeth when using lingual braces would help understand the biomechanics of this system. The in vivo measurements from orthodontic treatment are difficult to quantify and are complicated by variations in patient specific factors. Examples of patient specific factors that contribute to the difference in expression of orthodontic treatment are: genetic factors, gingival biotype, bone density parameters, oral hygiene, salivary content, masticatory function, muscle pressures, patient specific tooth and root anatomy, etc. Therefore, in vitro study designs may be beneficial to allow quantitative data collection for different treatment mechanics in a controlled environment.

The orthodontic simulator (OSIM) is an in vitro experimental device that was created and validated at the University of Alberta[16,17] to measure the three dimensional (3D) forces and moments experienced by tooth simulations as a result of orthodontic treatment mechanics. The OSIM allows the in vitro measurement of forces and moments on each tooth in the dental arch simultaneously. The OSIM was used for this study to analyze the biomechanical forces and moments of a lingual bracket system used to generate space for a crowded maxillary dentition.

Crowded teeth with insufficient space is a common component of many dental malocclusions. Two possible types of orthodontic treatment mechanics to create space for crowded teeth are: open coil springs and archwire stops (Fig 1.1). Open coil springs generate space by pushing the teeth apart on either side of the springs. Open coil springs are cut to an appropriate length, and then compressed and inserted between the teeth where space is needed. As the open coils decompress and return to their original uncompressed length, the teeth on either side of the coils are pushed apart, creating space. Archwire stops are another possible method for creating space. Archwire stops are small rectangular clips that can be crimped onto an archwire and secured in position. When archwire stops are used for space generation, an extra length of archwire is incorporated between two stops. As the archwire is ligated into the orthodontic brackets, the extra length of wire between the stops is compressed. As this additional length of archwire decompresses to return to its original shape, the teeth are pushed outward to create the space needed. There are no previous studies that compare the differences between these treatment mechanics when using lingual braces. This is an important area to explore because these mechanics are commonly used in clinical orthodontic treatment. This study will investigate the biomechanics of both open coils and archwire stops when using lingual brackets.

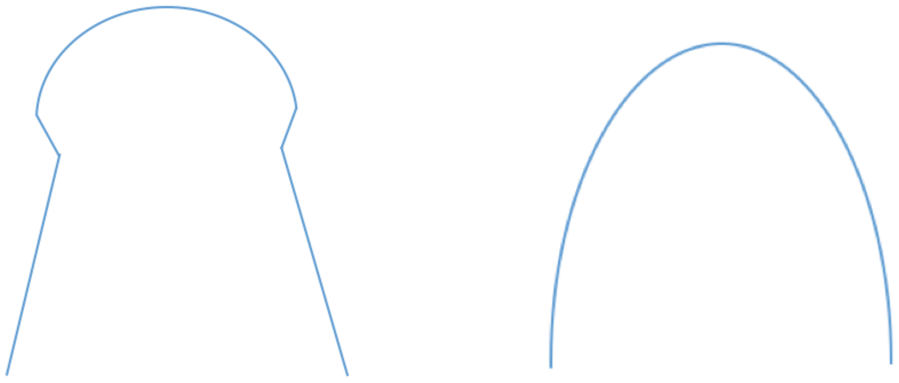


a) *b)*

Figure 1.1 Mechanics used for generating space in a dental arch

a) Archwire stops b) Open coil spring

The difference in anatomy on the lingual surfaces of the teeth has led to the development of two different lingual archwire shapes: 1. Straight archwires, 2. Mushroom archwires (Fig. 1.2). Straight archwires have a continuous parabolic shape and are similar to the archwires used in labial treatment. The straight archwires are not customized in shape for the lingual arch form, therefore an increased thickness of bonding material is needed to compensate for the shape of the lingual surfaces of the teeth[18]. Mushroom archwires were developed specifically for lingual orthodontic treatment[8]. The mushroom archwires have a bend between the canines and first premolars to follow the anatomy of the lingual surfaces of the teeth and allow closer adaptation of the archwire to the teeth in that area[19]. The differences in shape between the straight and mushroom archwires may affect the biomechanical forces and moments experienced by the teeth during orthodontic treatment[19]. There is minimal research comparing straight archwires to mushroom archwires[19,20], and currently there is no research comparing straight archwires to mushroom archwires when using space generation mechanics. This study will analyze both straight and mushroom archwires in combination with space generation mechanics and lingual brackets.



a) *b)*

Figure 1.2 Shapes of archwires used for lingual brackets

a) Mushroom archwire b) Straight archwire

There is minimal literature available regarding the biomechanics of lingual orthodontic treatment. Understanding the forces and moments experienced by the teeth during orthodontic treatment is important for maintaining the health of the teeth and surrounding structures throughout treatment. Studying the 3D forces and moments experienced by the teeth during lingual braces treatment would provide a more thorough understanding of the lingual biomechanical force systems. Understanding the effects and biomechanical differences between different lingual archwire shapes and treatment mechanics for space generation will lead to a better knowledge base for understanding how forces and moments can be applied to the teeth to produce tooth movement that is clinically beneficial, while minimizing potential detrimental side effects to the teeth and surrounding structures.

1.2 Study Design

This study was designed to determine the forces and moments generated by lingual brackets when using different archwire types and different space generation treatment mechanics for a crowded dentition. The forces and moments are measured using the OSIM in vitro apparatus. This study compares four different experimental groups:

1. Straight archwires with NiTi coils
2. Straight archwires with stops
3. Mushroom archwires with NiTi coils
4. Mushroom archwires with stops

1.3 Research Questions

The research aim of this study is to determine the differences in the forces and moments of interest experienced by the upper first premolars (tooth #1.4 and tooth #2.4) and upper lateral incisors (tooth #1.2 and tooth #2.2) between the two different treatments (coils and stops) and the two different archwires (straight archwires and mushroom archwires). These specific teeth were chosen for study because they were located closest to where the treatment mechanics were applied. Specifically, forces and moments in the mesial-distal direction and buccal-lingual direction will be analyzed. Intrusion and extrusion forces will not be included in the analysis because they are not the main direction of interest in this study.

Primary Research Questions:

1. Are there differences in the forces or moments of interest experienced by the upper first premolars between the different treatment and archwire groups?

2. Are there differences in the forces or moments of interest experienced by the upper lateral incisors between the different treatment and archwire groups?

Secondary Research Questions:

1. If there are statistically significant differences in the primary research questions, what are the magnitude of these differences?

1.4 Research Objectives

The objectives of this research study are to determine if there are differences in the forces or moments of interest between the different treatment mechanics and different archwire shapes. This information is beneficial for clinical orthodontic treatment because it may give insight into which appliances would provide the most clinically beneficial outcomes with the least undesirable side effects on the teeth and surrounding tissues.

References:

1. Kitaura H, Kimura K, Ishida M, Sugisawa H, Kohara H, Yoshimatsu M et al. Effect of Cytokines on Osteoclast Formation and Bone Resorption during Mechanical Force Loading of the Periodontal Membrane. Scientific World Journal. 2014; 2014: 617032.

2. Taibah SM, Al-Hummayani FM. Effect of malocclusion on the self-esteem of adolescents. J Orthod Sci. 2017;6(4): 123–128.

3. Gameiro GH, Magalhaes IB, Szymanski MM, Andrade AS. Is the main goal of mastication achieved after orthodontic treatment? A prospective longitudinal study. Dental Press J Orthod. 2017;22(3): 72–78.

4. Alsulaiman AA, Kaye E, Jones J, Cabral H, Leone C, Will L et al. Incisor malalignment and the risk of periodontal disease progression. Am J Orthod Dentofacial Orthop. 2018;153(4):512-522

5. Ogura M, Kamimura H Fau - Al-Kalaly A, Al-Kalaly A Fau - Nagayama K, Nagayama K Fau - Taira K, Taira K Fau - Nagata J, Nagata J Fau - Miyawaki S et al. Pain intensity during the first 7 days following the application of light and heavy continuous forces. Eur J Orthod. 2009;31(3):314-9

6. Talic NF. Adverse effects of orthodontic treatment: A clinical perspective. The Saudi dental journal 2011;23:55-59.

7. Rosvall MD, Fields Hw Fau - Ziuchkovski J, Ziuchkovski J Fau - Rosenstiel SF, Rosenstiel Sf Fau - Johnston WM, Johnston WM. Attractiveness, acceptability, and value of orthodontic appliances. Am J Orthod Dentofacial Orthop. 2009;135(3):276.e1-12

8. Fujita K. New orthodontic treatment with lingual bracket mushroom arch wire appliance. Am J Orthod. 1979;76(6):657-75.

9. McDonald F, Cobourne M. Adult orthodontics: perils and pitfalls. Prog Orthod. 2007;8(2):308-13.

10. Kairalla Sa Fau - Galiano A, Galiano A Fau - Paranhos LR, Paranhos LR. Lingual orthodontics as an aesthetic resource in the preparation of orthodontic/surgical treatment. Int J Orthod Milwaukee. 2014;25(2):31-5.

11. Liang W, Rong Q Fau - Lin J, Lin J Fau - Xu B, Xu B. Torque control of the maxillary incisors in lingual and labial orthodontics: a 3-dimensional finite element analysis. Am J Orthod Dentofacial Orthop. 2009;135(3):316-22

12. George RD, Hirani S. Fully-customized lingual appliances: how lingual orthodontics became a viable treatment option. J Orthod. 2013;40 Suppl 1:S8-13

13. Shpack N, Geron S, Floris I, Davidovitch M, Brosh T, Vardimon AD. Bracket Placement in Lingual vs Labial Systems and Direct vs Indirect Bonding. The Angle Orthodontist 2007;77:509-517.

14. Lombardo L, Wierusz W Fau - Toscano D, Toscano D Fau - Lapenta R, Lapenta R Fau - Kaplan A, Kaplan A Fau - Siciliani G, Siciliani G. Frictional resistance exerted by different lingual and labial brackets: an in vitro study. Prog Orthod. 2013;14:37.

15. Lombardo L, Arreghini A Fau - Al Ardha K, Al Ardha K Fau - Scuzzo G, Scuzzo G Fau - Takemoto K, Takemoto K Fau - Siciliani G, Siciliani G. Wire load-deflection characteristics relative to different types of brackets. Int Orthod. 2011;9(1):120-39

16. Badawi H. The use of multi-axis force transducers for orthodontic force and moment identification. Edmonton, AB, Canada: University of Alberta 2009. [thesis]

17. Badawi HM, Toogood RW, Carey JPR, Heo G, Major PW. Three-dimensional orthodontic force measurements. American Journal of Orthodontics and Dentofacial Orthopedics 2009;136:518-528.

18. Abdi AHA-Ohoo, Motamedian SR, Balaghi E, Nouri MA-OhooX. The effect of occlusogingival placement of clinical bracket points on the adaptation of a straight wire to the lingual arch form. Korean Journal of Orthodontics. 2018;48(4):236

19. Owen B, Gullion G, Heo G, Carey JP, Major PW, Romanyk DL. Measurement of forces and moments around the maxillary arch for treatment of a simulated lingual incisor and high canine malocclusion using straight and mushroom archwires in fixed lingual appliances. Eur J Orthod. 2017;39(6):665-672

20. Lombardo L, Carlucci A, Palone MA-Ohoo, Mollica F, Siciliani G. Stiffness comparison of mushroom and straight SS and TMA lingual archwires. Prog Orthod. 2016;17(1):27

Chapter 2 Literature Review

2.1 Introduction

Lingual orthodontic treatment with fixed appliances is a relatively recent addition to regularly used orthodontic appliances. Lingual orthodontic treatment involves bonding the brackets on the inside surfaces of the teeth. There may be esthetic and social advantages for patients with lingual braces because the orthodontic appliances are less visible[1]. It is becoming more common that adult patients are seeking orthodontic treatment, and many adult patients have esthetic and social concerns[2] [3]. Lingual braces may provide a good option for patients seeking an esthetic approach to treatment[1] [3] .

There are biomechanical considerations that are different when comparing lingual braces to traditional labial braces[4] [5] [6] [7]. These considerations include differences in arch shape[4], arch size[4], anatomy of the surfaces of the teeth[8], inter-bracket distance[9] [5], and relationship to the center of resistance of the teeth[4]. The difference between lingual and labial braces systems are important to study because they will influence the forces and moments experienced by the teeth.

There is minimal literature available with respect to the biomechanics of lingual orthodontic treatment. There have been previous in vitro studies designed to quantitatively measure the forces and moments experienced by the teeth during labial and lingual treatment mechanics[10] [11] [12] [13] [14]. However, there are still many biomechanical areas of lingual braces treatment that have not been studied.

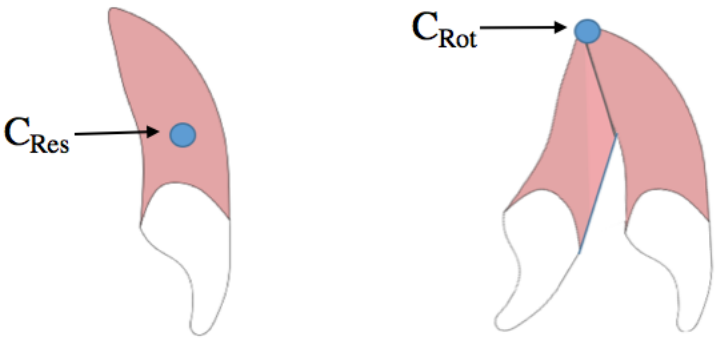
2.2 Biology of Tooth Movement

Understanding the biomechanics of orthodontic treatment is important to ensure that the health of the teeth and surrounding tissues are maintained throughout treatment. Each tooth is surrounded by a periodontal ligament (PDL) which attaches the tooth to the alveolar bone[15]. The PDL contains fibrous connective tissues, neural tissue, and vascular tissues[15]. The PDL helps absorb the impact of forces on the tooth during masticatory functions[15]. When a tooth experiences a force from an orthodontic appliance, the forces are transmitted to the PDL around the tooth. This force on the PDL stimulates osteoclasts and osteoblasts in the alveolar bone to facilitate bone remodeling[15]. The compression side of the PDL stimulates osteoclasts from the vascular tissues in the PDL[16] to resorb the lamina dura bone[15]. Stretching of the PDL on the opposing tension side stimulates osteoblasts to form additional bone[15]. This combination of osteoclastic and osteoblastic activity is responsible for allowing the tooth to move through the alveolar bone[15]. When bone remodeling occurs in this way, it is known as frontal resorption[16]. Frontal resorption is induced by light to moderate forces and occurs when the osteoclasts are stimulated in the PDL; the bone remodeling begins ahead of the compressed surface of the PDL[16]. If the tooth experiences forces that are too heavy, the PDL can become compressed and pushed against the alveolar bone which may occlude the blood vessels on that side[15]. When the blood vessels become occluded on the compression side it can cause cell death in that area and result in hyalinization and sterile necrosis of the PDL[15]. When this happens, osteoclasts must be recruited from adjacent tissues that are further away, and undermining resorption occurs instead of frontal resorption[15]. Undermining resorption slows tooth movement because both the lamina dura and hyalinized PDL area must be removed before the tooth can move[17]. Forces too large in magnitude can also lead to increased root resorption of the teeth[18]. Therefore, application of forces that are too heavy have the potential to damage the tooth and adjacent structures[18] and can also increase the treatment time as a result of the delayed tooth movement[17]. Understanding orthodontic forces and moments applied during treatment is important to preserve the health of the teeth and surrounding structures throughout treatment.

2.3 Biomechanics of Tooth Movement

An important concept to understand when describing tooth movement is the center of resistance (Fig 2.1a). In contrast to free bodies, teeth are restrained bodies through the surrounding periodontal tissues and alveolar bone[19]. The center of resistance of the tooth is the point in which, if a line of action of a force passes directly through that point, would produce translational (bodily) movement[19]. The center of resistance of a tooth depends on the length of the root of the tooth, and the amount of the tooth that is covered by the periodontal and bony tissues[19]. Therefore, the center of resistance varies for each tooth, but is usually found approximately one third to one half of the way down the root of the tooth[19].

Another important concept to understand is the center of rotation (Fig 2.1b). For orthodontic tooth movement, the center of rotation is the point at which the tooth rotates around in response to an applied force or moment [19] . Therefore, the center of rotation can vary depending on the specific arrangement of forces are acting on the tooth, and can occur beyond the tooth itself[19]. When discussing orthodontic tooth movement, the movements are often discussed in relation to the center of resistance and center of rotation.



a) *b)*

Figure 2.1 Difference between Center of Resistance and Center of Rotation on a tooth

a) Center of Resistance (CRes) b) Center of Rotation (CRot)

(Note that this is one example of a Center of Rotation. The Center of Rotation is dependent on the specific forces and moments experienced by the tooth)

Understanding how a tooth will respond to applied force systems will decrease the chance of unwanted tooth movements occurring. If unwanted tooth movements occur, they will need to be corrected which may increase the treatment time or result in round tripping of the teeth. Excessive round tripping of the teeth can lead to effects such as loss of pulp vitality or root resorption[18].

Understanding the ideal force levels to move teeth is also important to maintain the health of the teeth and surrounding structures throughout treatment. Von Fraunhofer et al.[20] described optimal tooth movement forces to range from 75-100g (0.75-1.0N). The results from a systematic review published about the optimal force magnitudes for tooth movement found that there was very minimal literature available on this topic, and that more well designed studies are needed[21]. The systematic review was not able to provide a clear answer for optimal orthodontic force levels because a meta-analysis could not be performed[21]. Historically, Schwartz[22] described that force levels should be less than the amount to obstruct capillary blood flow in the PDL, which is 32mmHg. However, the specific type of tooth movement affects the amount of recommended force levels[21]. Proffit et al.[23]provided a range of force that are considered to be optimal for certain tooth movements: 30-60g for tipping, rotation, and extrusion, 50-100g for root uprighting, and 70-120g for translation. Smith et al.[19] and Proffit et al.[23] highlight that there is much individual variation in the biologic response to applied forces on the teeth, and therefore the optimal force for tooth movement may vary from patient to patient. Previous studies [24] [25] [26] have reported that minimum forces and moments necessary to produce tooth movement are >0.2N and >3-5Nmm respectively. These reported thresholds for tooth movement are based on historical values and expert opinion rather than well designed evidence based studies. However, these values have been generally accepted by the orthodontic literature as the thresholds for inducing tooth movement. Although the level of evidence to support these thresholds are low, they are the best available data at present for understanding minimum thresholds for tooth movement. Therefore, because these are the generally accepted values at present, and to be consistent with previous studies on this topic, we will use the values described by previous literature[24] [25] [26] of minimum forces necessary to produce tooth movement of >0.2N, and moments of >3-5Nmm.

There are many differences in the biomechanics of lingual orthodontic treatment compared to traditional labial orthodontic treatment[4] [5] [6] [7]. The size and shape of the lingual arch form is different compared to the labial arch form (Fig 2.2). The lingual arch form is more constricted[4] and has a step between the canines and first premolars due to the anatomy of the lingual surfaces of the teeth. When brackets are placed on the lingual surfaces of the teeth they have decreased inter-bracket distance[5,9]. The decreased inter-bracket distance (Fig 2.2) decreases the length of archwire between brackets. This decreased length of archwire causes the archwire segments to be more stiff, and can lead to higher forces and moments experienced by the teeth for the same amount of archwire deflection [5 9].

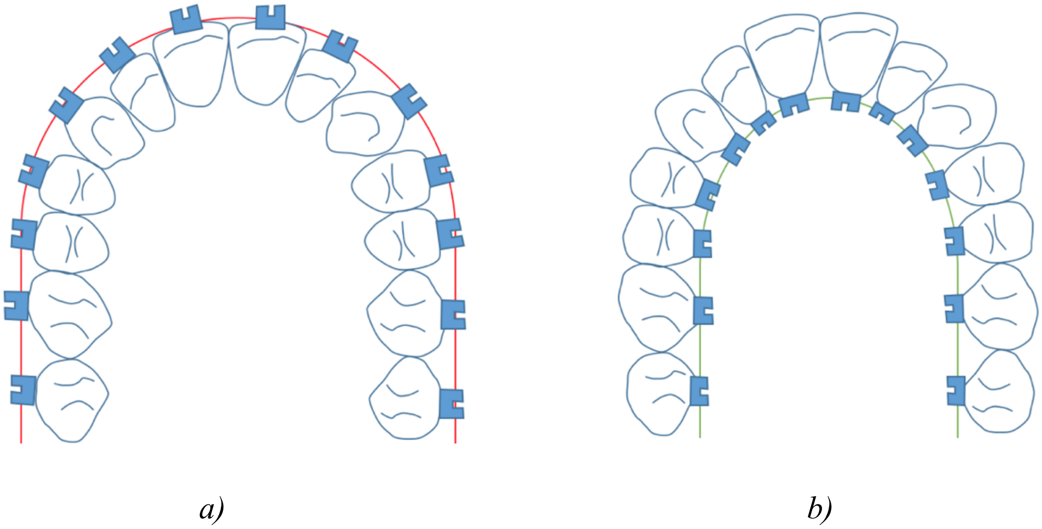


Figure 2.2 Arch forms with labial and lingual brackets

a) Labial Brackets: Arch form is wider in shape and greater distance between brackets

b) Lingual Brackets: Arch form is more constricted and decreased distance between brackets

The anatomy of the lingual surfaces of the anterior teeth are concave, compared to the convex shape of labial surfaces[8]. This concave shape affects the adaptation of the bracket to the tooth surface[8]. Lingual brackets also tend to be placed higher vertically on the anterior teeth, which may be closer to the center of resistance of the teeth compared to labial brackets (Fig 2.3)[4]. The distance from the application of the force to the center of resistance of the teeth affects resultant forces and moments and therefore affects the specific tooth movements that will occur.

Mechanically, having the brackets closer to the center of resistance may make it easier to achieve certain movements. There is limited research about the biomechanics of lingual orthodontic treatment, therefore studying the forces and moments during lingual treatment mechanics would contribute to this understanding.

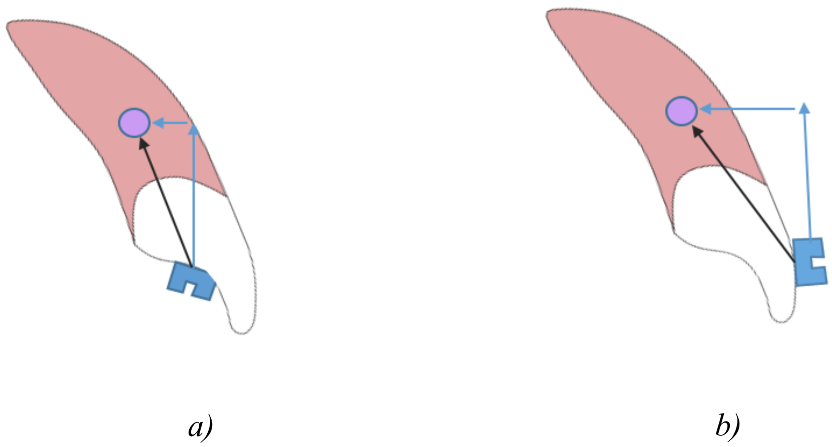

a) *b)*

Figure 2.3 Bracket location and Center of Resistance

a) Labial Bracket in relation to Center of Resistance

b) Lingual Bracket in relation to Center of Resistance

2.4 Lingual Orthodontic Treatment

The introduction of lingual braces originated with Dr. Kinya Fujita and Dr. Craven Kurz who separately began developing lingual brackets[27 28]. The initial acceptance of lingual brackets by clinicians eventually decreased as certain challenges with the appliance arose. Challenges with the initial lingual appliances included difficulty in bracket placement[28], frequent debonding of brackets[28], difficulty ligating archwires[26], and less predictable results compared to traditional labial brackets[28]. Despite the initial challenges with lingual braces, recent advances have increased their popularity and use among clinicians[28 4]. Traditional lingual braces treatment involved using stock brackets with the clinician placing brackets on each individual tooth at the initial bonding procedure. There is now technology that can create customized lingual brackets based on the anatomy of an individual patient[4 28], and when used with indirect bonding procedures, have increased the precision and predictability of lingual fixed appliances[28]. With indirect bonding, the bracket placement can be done on the computer, and then is transferred to the patient's mouth through a printed template. The development of self-ligating lingual brackets[28] and systems that include machine pre-bent archwires[28] have also improved the ease and efficiency of lingual appliances. The improved technology has resulted in decreased bond failures[4], decreased bracket size[28], decreased errors in bracket positioning through indirect bonding[28 4], and improved precision of the slot size of lingual brackets[4]. This technology has started to increase the popularity of lingual braces among clinicians[28 4].

In 2013, George et al.[4] published an article discussing the advantages of updated lingual braces systems. Different biomechanical concepts that clinicians face with lingual braces systems are highlighted in this article. Arch expansion to correct a crowded dentition may be more effective with lingual braces systems because the archwire is more compressed compared to labial archwires[4]. The transverse expansion associated with lingual braces has less anterior incisor tipping compared to labial systems[4]. Resolving overbite in deep bite patients is less complicated with lingual braces because the patients occlude on the anterior lingual brackets which opens the bite posteriorly[4]. This has two effects that are beneficial for deep bite correction: intrusion of the incisors, and facilitates extrusion of the posterior teeth[4]. With lingual braces, the brackets are placed higher vertically on the tooth than labial braces, which is closer to the center of resistance of the tooth, and therefore may have advantages for certain types of tooth movements[4].

Geron et al. in 2014[6] used a theoretical mathematical model to assess the differences between labial and lingual brackets when using intrusion and extrusion forces on maxillary central incisors. This article reported four differences in the biomechanics of lingual brackets compared to labial brackets. First, there was less crown tipping observed when vertical forces were applied to lingual compared to labial brackets[4]. This finding was attributed to the difference in bracket position relative to the center of resistance for labial and lingual brackets. The lingual brackets were closer to the center of resistance; therefore, less resultant moment was observed when using lingual brackets compared to labial[4]. As a result of this, torque application may be more difficult with lingual brackets[4]. This finding is consistent with Pol et al. in 2018[7] which used three-dimensional finite element analysis to analyze the differences in torque expression when using intrusion mechanics for lingual and labial appliances. This study reported that when intrusion forces were applied to maxillary central incisors, there was more labial crown torque observed with labial compared to lingual brackets[7]. However, due to improvements in the technology of lingual braces with customized appliances, successful torque expression using lingual brackets can be achieved[29]. The second difference found by Geron et al.[6] was that the arch dimensions of the lingual surfaces of the teeth were more constricted than the labial surfaces, therefore the inter-bracket distances were decreased between lingual brackets[6]. The result of this finding is that the load deflection rate of the wire is increased with lingual brackets compared to labial systems for the same amount of tooth displacement[6]. This finding is supported by the results of the study by Lombardo et al. in 2011[5]. The third difference found by Geron et al.[6] was that the anatomy of the lingual surfaces of the teeth were more variable compared to the labial surfaces. The extent of concavity of the lingual surfaces of the teeth is greater than the extent of convexity of the labial surfaces. As a result, any differences in bracket positioning will result in greater changes in tooth position when using lingual compared to labial brackets[6]. The fourth difference reported by Geron et al.[6] is that labial brackets are bonded on the surfaces of the teeth that are being aligned, compared to lingual brackets which are bonded on the opposite surfaces[6]. Therefore, any alteration in bracket position on the lingual surface will create increased resultant tooth movement compared to the same alteration made with labial brackets[6].

Differences in bracket dimension between lingual and labial brackets was discussed by Park et al.[30]. The decreased mesial-distal dimension of lingual brackets may result in less tipping and rotational control compared to labial brackets[30]. The smaller inter-bracket distance with lingual brackets may increase friction when archwires are ligated in lingual brackets[30]. When an identical archwire is used with lingual brackets and labial brackets, the archwire may be more stiff when used with the lingual brackets due to the decreased inter-bracket distances[30]. Lombardo et al.[5] also discussed the differences in bracket dimension between lingual and labial brackets, which may affect archwire sequencing during treatment.

The improvement of the technology of lingual braces has expanded the complexity of cases that can be treated with lingual braces[28]. Articles have been published that demonstrate the use of lingual brackets in combination with extraction treatment[31 32] and orthognathic surgery[3 33]. Studies that used 3D finite element analysis to analyze retraction mechanics[34 35 36] reported that the lingual position of the brackets affects the stresses observed surrounding the teeth due to the difference in the line of action of the force in relation to the center of resistance of the teeth[34 35]

[36]. Therefore, lingual brackets can be used to treat these more complex malocclusions as long as the biomechanical differences are understood.

A systematic review published in 2016[37] assessed the results of orthodontic treatment with lingual braces. This review reported that treatment with lingual orthodontic braces showed promising results with regard to accomplishing the planned treatment goals and having less tooth decalcifications at the end of treatment[37]. However, due to the small number of studies and risk of bias, further well designed studies are needed[37].

2.5 Lingual Braces Compared to Labial Braces

In 2005, a study was published that compared labial and lingual brackets using straight wires to compare the initial forces applied[38]. This study used the Robotic Measurement System (RMS) to measure forces and moments on dental casts with both labial and lingual brackets. The results of this study found that the initial levelling forces were similar between lingual and labial appliances[38].

A study that compared lateral cephalometric landmarks before and after treatment with labial and lingual braces found that there were no meaningful differences in the lateral cephalometric landmarks or measurements between the labial and lingual appliances[39]. Therefore, the same treatment goals were achieved using either appliance[39].

A systematic review published in 2016[40] compared lingual to labial braces treatment. This review reported that patients with lingual braces had more significant soreness, issues with speech, trouble eating, reduced intermolar width, enlarged intercanine width, and less mesial movement of the upper first molars when closing space compared to labial braces[40]. The overall quality of evidence for the included studies was low, therefore, the results have to be interpreted with caution and specific recommendations could not be made[40].

Another systematic review and meta-analysis published in 2017 compared differences in orthodontic treatment using labial and lingual braces[41]. This review found that there were no statistically significant differences between lateral cephalometric radiographic measurements between lingual and labial braces[41]. This review mentioned a tendency toward lingual braces expressing increased lingual crown torque due to the observation of increased measurements of the interincisal angle and decreased sella-nasion to maxillary central incisor angles, but these observations were not statistically significant[41]. This article concludes that because only two articles were included in the meta-analysis, the findings should be interpreted with caution[41].

Comparison of the dental and skeletal outcomes when using a Herbst appliance with either lingual or labial braces was published in 2016[42]. This study reported that most treatment effects that were compared had similar results when the Herbst appliance was used with either lingual or labial brackets[42].

A study by Nassif et al. in 2017[43] found that there were no statistically significant differences between lingual and labial braces on root resorption of the maxillary anterior teeth with crowded incisors.

2.6 In Vitro Methods for Studying Orthodontic Biomechanics

In vitro studies have been conducted to assess the forces and moments that occur during orthodontic tooth movement. Most of the studies include specialized designs of experimental devices to measure the force and moment data during application of simulated orthodontic tooth movements.

Bourauel et al.[10] developed an in vitro apparatus in 1992, the Orthodontic Measurement and Simulation System (OMSS), to measure 3D orthodontic forces and moments of two teeth. The apparatus contained sensors that simultaneously collected the force and moment data from the two teeth and transmitted the information to a computer to be analyzed[10]. This apparatus included a heat chamber set to 37 degrees Celsius to simulate the conditions of Nickel Titanium wires in the oral cavity[10]. The OMSS was used in 2014 to compare lingual and labial brackets in a simulated malocclusion with a lingually displaced maxillary lateral incisor[44]. The results of this study found that lingual appliances had increased force values and decreased moment values compared to the labial appliances[44]. The OMSS was used in 2017 by Alobeid et al.[11] to compare labial and lingual brackets using both conventional and self-ligating designs. The results of this study found that lingual brackets had increased force levels compared to labial brackets and that there were no significant differences between self-ligating and conventional designs[11]. In 2018, Alobeid et al. studied the results between labial and lingual self-ligating and conventional brackets on initial alignment of the teeth using the OMSS[45]. The results from this study reported that lingual brackets were less successful in providing vertical and anterior-posterior control of the teeth compared to labial brackets[45].

In 1999, Mengi et al.[12] used an in vitro machine to test the 3D forces and moments of different wire loop configurations used in clinical orthodontics. The different loop configurations were inserted into the machine, and strain gauges converted the force and moment data experienced by the machine into electrical impulses to generate a graphical analysis of the results[12]. This allowed comparison of the different wire loop designs and only measured the forces and moments of the wire loops; the loops were not attached to teeth in a dental arch[12].

Kuo et al.[13] developed an in vitro orthodontic simulator in 2001 to measure forces and moments for a simulated maxillary dental arch consisting of: four anterior teeth, second premolars, and first molars. This orthodontic simulator model was used to measure forces and moments during retraction of the four anterior teeth during a simulated extraction case[13]. This orthodontic simulator did not include the first premolars.

Mencattelli et al. in 2017[14] designed an in vitro apparatus to measure the forces and moments of three anterior plaster teeth using anchorage to simulate miniscrews to close extraction space. The limitations of this apparatus is that it only measured the forces and moments of three teeth.

2.7 Orthodontic Simulator (OSIM)

The Orthodontic Simulator (OSIM) was developed at the University of Alberta[46 47]. This was the first in-vitro machine to measure 3D forces and moments of all teeth in a single dental arch simultaneously[47]. This machine includes metal tooth simulations of a single dental arch including the central incisors to the second molars bilaterally. Validation of the OSIM was established through development and studies at the University of Alberta[46 47].

Since the development of the OSIM, it has been used to study the biomechanics of many different simulated orthodontic clinical situations. In 2011, Fok et al[48 49] used the OSIM to analyze a simulated clinical orthodontic situation with a high canine. Both passive self-ligation[48] and conventional elastic ligation[49] were used with labial brackets. The conclusion of these studies suggested that a potential benefit to the passive self-ligation method may be the decreased transmission of undesirable forces and moments to the other teeth around the arch[48 49]. In 2014 Major et al.[50] analyzed different sizes of copper nickel titanium (CuNiTi) wires with the same simulated clinical situation of a high canine and found that increasing the wire size did not have a proportional relationship to the forces and moments experienced by the teeth.

In 2014, Seru et al.[51] used the OSIM to study the forces and moments associated with passive and elastic ligation of a lingually positioned maxillary incisor. The results of this study reported that elastic ligation was associated with increased maximum forces and moments, and that the side effects of these forces and moments were spread to more additional teeth along the arch[51].

The OSIM was used in 2016 by Lee et al.[52] to study the forces on the teeth in the maxillary arch when using dental and skeletal anchorage during retraction of the anterior segment after extraction of first premolars. The results of this study reported that while skeletal anchorage decreased the force magnitudes on the posterior teeth, skeletal anchorage also increased the vertical force magnitudes on the anterior teeth[52].

The teeth on the OSIM were designed with lingual anatomy in 2017, when Owen at al.[53] studied the biomechanics of lingual orthodontic appliances. This study included the assessment of lingual straight archwires and lingual mushroom archwires with a gingivally positioned maxillary canine and a lingually positioned maxillary lateral incisor[53]. The results of this study described that straight archwires had increased forces and moments compared to the mushroom archwires for both malocclusions[53].

2.8 Space Generation Treatment Mechanics

There are many different methods of treatment mechanics for generating space for a crowded dentition in clinical orthodontics. Of the many methods possible, two specific types are Nickel Titanium (NiTi) coils and crimpable archwire stops. NiTi coils are compressed between the teeth where space is needed, and as the coils decompress and return to their original length, they push the adjacent teeth apart which creates the desired space. Archwire stops are small metal clips that are crimped onto the archwire so that they cannot move. The stops are crimped onto the archwire with an extra length of wire between the stops, which is then ligated into the brackets between the stops. As this extra length of wire expresses, it expands the arch to generate the desired space that is needed. Although these two methods are both routinely used in clinical orthodontics, there is no previous literature about crimpable archwire stops, and no literature comparing archwire stops to NiTi coils for space generation.

There is literature available on the mechanical properties of NiTi coils themselves[54] [20, 55-57] [58], but minimal literature on the effects they have on the adjacent teeth. Optimal forces for orthodontic treatment are considered as in the range of 75-100g[20], and being light and continuous in nature[20]. The general conclusions of these studies reported that NiTi coil springs deliver more optimal force levels over a long duration of action than stainless steel springs[20]. The majority of the current literature about NiTi coil springs involves closed coil springs used in retraction mechanics.

2.9 Lingual Archwires

The shape of the dental arch is different on the lingual surfaces compared to the labial surfaces. The labial surfaces of a well aligned dental arch are a smooth continuous parabolic shape. The lingual surfaces of the teeth have a distinct step between the canines and first premolars. Therefore, there are two types of archwires used with lingual braces: straight archwires and mushroom archwires[1]. Straight archwires have a continuous parabolic shape, and mushroom archwires have a step bend between the canines and first premolars to replicate the lingual anatomical arch form[1]. The shape of the mushroom archwire allows closer adaptation of the archwire to the teeth in the canine and first premolar area. A previous study[53] looked at the differences between round NiTi straight and mushroom lingual archwires. The results of this study reported that the straight archwires showed increased force magnitudes compared to the mushroom archwires[53]. Lambardo et al.[59] compared straight and mushroom stainless steel and beta titanium (TMA) archwires and found that every maxillary straight archwire had significantly increased stiffness compared to the mushroom archwires. This study found that the mandibular archwires had minimal differences between the straight and mushroom shape[59].

2.10 Clinically Significant Tooth Movement

When providing clinical orthodontic treatment, it is important to understand the ideal forces and moments to apply to the teeth. If forces or moments are too low, the teeth may not move to the desired locations. If the forces or moments are too high, they may cause damage to the teeth and surrounding structures[15 18 60]. Understanding clinically relevant tooth movement forces and moments are also important for interpreting data from in vitro studies. It has been reported that forces above 0.2N[24] and moments above 3-5Nmm[25, 26] cause tooth movement. The data to authenticate the minimum forces and moments required to cause tooth movement is minimal, therefore this paper will consider forces greater than 0.2N and moments greater than 3Nmm to be clinically significant.

References:

1. Fujita K. New orthodontic treatment with lingual bracket mushroom arch wire appliance. Am J Orthod. 1979;76(6):657-75.

2. McDonald F, Cobourne M. Adult orthodontics: perils and pitfalls. Prog Orthod. 2007;8(2):308-13.

3. Kairalla Sa Fau - Galiano A, Galiano A Fau - Paranhos LR, Paranhos LR. Lingual orthodontics as an aesthetic resource in the preparation of orthodontic/surgical treatment. Int J Orthod Milwaukee. 2014;25(2):31-5.

4. George RD, Hirani S. Fully-customized lingual appliances: how lingual orthodontics became a viable treatment option. J Orthod. 2013;40 Suppl 1:S8-13.

5. Lombardo L, Arreghini A Fau - Al Ardha K, Al Ardha K Fau - Scuzzo G, Scuzzo G Fau - Takemoto K, Takemoto K Fau - Siciliani G, Siciliani G. Wire load-deflection characteristics relative to different types of brackets. Int Orthod. 2011;9(1):120-39

6. Geron S, Romano R Fau - Brosh T, Brosh T. Vertical forces in labial and lingual orthodontics applied on maxillary incisors--a theoretical approach. Angle Orthod. 2004 Apr;74(2):195-201.

7. Pol TR, Vandekar M, Patil A, Desai S, Shetty V, Hazarika S. Torque Control During Intrusion on Upper Central Incisor in Labial and Lingual bracket System - A 3D Finite Element Study. J Clin Exp Dent. 2018;10(1):e20-e24.

8. Shpack N, Geron S, Floris I, Davidovitch M, Brosh T, Vardimon AD. Bracket Placement in Lingual vs Labial Systems and Direct vs Indirect Bonding. The Angle Orthodontist 2007;77:509-517.

9. Lombardo L, Wierusz W Fau - Toscano D, Toscano D Fau - Lapenta R, Lapenta R Fau - Kaplan A, Kaplan A Fau - Siciliani G, Siciliani G. Frictional resistance exerted by different lingual and labial brackets: an in vitro study. Prog Orthod. 2013;14:37

10. Bourauel C, Drescher D Fau - Thier M, Thier M. An experimental apparatus for the simulation of three-dimensional movements in orthodontics. J Biomed Eng. 1992;14(5):371-8.

11. Alobeid A, El-Bialy T, Khawatmi S, Dirk C, Jager A, Bourauel C. Comparison of the force levels among labial and lingual self-ligating and conventional brackets in simulated misaligned teeth. Eur J Orthod. 2017;39(4):419-425.

12. Menghi C, Planert J Fau - Melsen B, Melsen B. 3-D experimental identification of force systems from orthodontic loops activated for first order corrections. Angle Orthod. 1999;69(1):49-57.

13. Kuo B, Takakuda K Fau - Miyairi H, Miyairi H. Development of an orthodontic simulator for measurement of orthodontic forces. J Med Dent Sci. 2001;48(1):15-21.

14. Mencattelli M, Donati E, Spinelli P, Cultrone M, Luzi C, Cantarella D et al. Measuring 3D-orthodontic actions to guide clinical treatments involving coil springs and miniscrews. Biomed Microdevices. 2017;19(1):14.

15. Kitaura H, Kimura K, Ishida M, Sugisawa H, Kohara H, Yoshimatsu M et al. Effect of Cytokines on Osteoclast Formation and Bone Resorption during Mechanical Force Loading of the Periodontal Membrane. Scientific World Journal. 2014;2014:617032.

16. Rygh P Fau - Bowling K, Bowling K Fau - Hovlandsdal L, Hovlandsdal L Fau - Williams S, Williams S. Activation of the vascular system: a main mediator of periodontal fiber remodeling in orthodontic tooth movement. Am J Orthod. 1986;89(6):453-68.

17. Meeran NA. Biological response at the cellular level within the periodontal ligament on application of orthodontic force - An update. Journal of orthodontic science 2012;1:2-10.

18. Talic NF. Adverse effects of orthodontic treatment: A clinical perspective. The Saudi dental journal 2011;23:55-59.

19. Smith Rj Fau - Burstone CJ, Burstone CJ. Mechanics of tooth movement.

20. von Fraunhofer JA, Bonds Pw Fau - Johnson BE, Johnson BE. Force generation by orthodontic coil springs. Angle Orthod. 1993;63(2):145-8

21. Ren Y, Maltha Jc Fau - Kuijpers-Jagtman AM, Kuijpers-Jagtman AM. Optimum force magnitude for orthodontic tooth movement: a systematic literature review. Angle Orthod. 2003;73(1):86-92.

22. A.M. Schwarz, Tissue changes incidental to orthodontic tooth movement, International Journal of Orthodontia, Oral Surgery and Radiography 18(4) (1932) 331-352.

23. W.R. Proffit, H.W. Fields, D.M. Sarver, Contemporary Orthodontics, Elsevier Health Sciences2014.

24. Nanda R. Biomechanics in Clinical Orthodontics Philadelphia: WB Saunders Co; 1996.

25. Gmyrek H, Bourauel C Fau - Richter G, Richter G Fau - Harzer W, Harzer W. Torque capacity of metal and plastic brackets with reference to materials, application, technology and biomechanics. J Orofac Orthop. 2002;63(2):113-28.

26. Casa MA, Faltin Rm Fau - Faltin K, Faltin K Fau - Sander FG, Sander Fg Fau - Arana-Chavez VE, Arana-Chavez VE. Root resorptions in upper first premolars after application of continuous torque moment. Intra-individual study. J Orofac Orthop. 2001;62(4):285-95.

27. Bonnick AM, Nalbandian M Fau - Siewe MS, Siewe MS. Technological advances in nontraditional orthodontics. Dent Clin North Am. 2011;55(3):571-84

28. Chatoo A. A view from behind: a history of lingual orthodontics. J Orthod. 2013;40 Suppl 1:S2-7.

29. Lossdorfer S, Bieber C Fau - Schwestka-Polly R, Schwestka-Polly R Fau - Wiechmann D, Wiechmann D. Analysis of the torque capacity of a completely customized lingual appliance of the next generation. Head Face Med. 2014;10:4.

30. Park JH, Lee Yk Fau - Lim B-S, Lim Bs Fau - Kim C-W, Kim CW. Frictional forces between lingual brackets and archwires measured by a friction tester. Angle Orthod. 2004;74(6):816-24.

31. Fujita K. Multilingual-bracket and mushroom arch wire technique. A clinical report. Am J Orthod. 1982;82(2):120-40.

32. Wilmes B, Nienkemper M Fau - Mazaud-Schmelter M, Mazaud-Schmelter M Fau - Renger S, Renger S Fau - Drescher D, Drescher D. Combined use of Beneslider and lingual braces, mechanical aspects and procedures. Orthod Fr. 2013;84(4):347-59.

33. Kyteas PG, McKenzie WS, Waite PD, Kau CH. Comprehensive treatment approach for condylar hyperplasia and mandibular crowding with custom lingual braces and 2-jaw surgery. Am J Orthod Dentofacial Orthop. 2017;151(1):174-185.

34. Lombardo L, Scuzzo G Fau - Arreghini A, Arreghini A Fau - Gorgun O, Gorgun O Fau - Ortan YO, Ortan Yo Fau - Siciliani G, Siciliani G. 3D FEM comparison of lingual and labial orthodontics in en masse retraction. Prog Orthod. 2014;15(1):38

35. Liang W, Rong Q, Lin J, Xu B. Torque control of the maxillary incisors in lingual and labial orthodontics: A 3-dimensional finite element analysis. American Journal of Orthodontics and Dentofacial Orthopedics 2009;135:316-322.

36. Sung SJ, Baik HS, Moon YS, Yu HS, Cho YS. A comparative evaluation of different compensating curves in the lingual and labial techniques using 3D FEM. American Journal of Orthodontics and Dentofacial Orthopedics 2003;123:441-450.

37. Mistakidis I, Katib H, Vasilakos G, Kloukos D, Gkantidis N. Clinical outcomes of lingual orthodontic treatment: a systematic review. European Journal of Orthodontics 2016;38:447-458.

38. Fuck LM, Wiechmann D Fau - Drescher D, Drescher D. Comparison of the initial orthodontic force systems produced by a new lingual bracket system and a straight-wire appliance. J Orofac Orthop. 2005;66(5):363-76

39. Gorman JC, Smith RJ. Comparison of treatment effects with labial and lingual fixed appliances. Am J Orthod Dentofacial Orthop. 1991;99(3):202-9.

40. Papageorgiou SNA-Ohoo, Golz L, Jager A, Eliades T, Bourauel C. Lingual vs. labial fixed orthodontic appliances: systematic review and meta-analysis of treatment effects. Eur J Oral Sci. 2016;124(2):105-18.

41. Ata-Ali F, Cobo T, De Carlos F, Cobo J, Ata-Ali J. Are there differences in treatment effects between labial and lingual fixed orthodontic appliances? A systematic review and meta-analysis. BMC Oral Health. 2017;17(1):133

42. Bock NC, Ruf S, Wiechmann D, Jilek T. Dentoskeletal effects during Herbst-Multibracket appliance treatment: a comparison of lingual and labial approaches. Eur J Orthod. 2016;38(5):470-7.

43. Nassif CE, Cotrim-Ferreira A, Conti ACCF, Valarelli DP, Cardoso MdA, Almeida-Pedrin RRd. Comparative study of root resorption of maxillary incisors in patients treated with lingual and buccal orthodontics. The Angle Orthodontist 2017;87:795-800.

44. Sifakakis I, Pandis N Fau - Makou M, Makou M Fau - Katsaros C, Katsaros C Fau - Eliades T, Eliades T Fau - Bourauel C, Bourauel C. A comparative assessment of forces and moments generated by lingual and conventional brackets. Eur J Orthod. 2013;35(1):82-6

45. Alobeid A, El-Bialy T, Reimann S, Keilig L, Cornelius D, Jager A et al. Comparison of the efficacy of tooth alignment among lingual and labial brackets: an in vitro study. Eur J Orthod. 2018;40(6):660-665.

46. Badawi H. The use of multi-axis force transducers for orthodontic force and moment identification. Edmonton, AB, Canada: University of Alberta 2009. [thesis]

47. Badawi HM, Toogood RW, Carey JPR, Heo G, Major PW. Three-dimensional orthodontic force measurements. American Journal of Orthodontics and Dentofacial Orthopedics 2009;136:518-528.

48. Fok J, Toogood Rw Fau - Badawi H, Badawi H Fau - Carey JP, Carey Jp Fau - Major PW, Major PW. Analysis of maxillary arch force/couple systems for a simulated high canine malocclusion: Part 1. Passive ligation. Angle Orthod. 2011;81(6):953-9.

49. Fok J, Toogood Rw Fau - Badawi H, Badawi H Fau - Carey JP, Carey Jp Fau - Major PW, Major PW. Analysis of maxillary arch force/couple systems for a simulated high canine malocclusion: Part 2. Elastic ligation. Angle Orthod. 2011;81(6):960-5.

50. Major PW, Toogood RW, Badawi HM, Carey JP, Seru S. Effect of wire size on maxillary arch force/couple systems for a simulated high canine malocclusion. J Orthod. 2014;41(4):285-91

51. Seru S, Romanyk DL, Toogood RW, Carey JP, Major PW. Effect of ligation method on maxillary arch force/moment systems for a simulated lingual incisor malalignment. Open Biomed Eng J. 2014;8:106-13

52. Lee D Fau - Heo G, Heo G Fau - El-Bialy T, El-Bialy T Fau - Carey JP, Carey Jp Fau - Major PW, Major Pw Fau - Romanyk DL, Romanyk DL. Initial forces experienced by the anterior and posterior teeth during dental-anchored or skeletal-anchored en masse retraction in vitro. Angle Orthod. 2017;87(4):549-555.

53. Owen B, Gullion G, Heo G, Carey JP, Major PW, Romanyk DL. Measurement of forces and moments around the maxillary arch for treatment of a simulated lingual incisor and high canine malocclusion using straight and mushroom archwires in fixed lingual appliances. Eur J Orthod. 2017;39(6):665-672.

54. Brauchli LM, Senn C Fau - Ball J, Ball J Fau - Wichelhaus A, Wichelhaus A. Force levels of 23 nickel-titanium open-coil springs in compression testing. Am J Orthod Dentofacial Orthop. 2011;139(5):601-5.

55. Schneevoigt R, Haase A Fau - Eckardt VL, Eckardt Vl Fau - Harzer W, Harzer W Fau - Bourauel C, Bourauel C. Laboratory analysis of superelastic NiTi compression springs. Med Eng Phys. 1999;21(2):119-25.

56. Manhartsberger C, Seidenbusch W. Force delivery of Ni-Ti coil springs. Am J Orthod Dentofacial Orthop. 1996;109(1):8-21.

57. Bourke A, Daskalogiannakis J Fau - Tompson B, Tompson B Fau - Watson P, Watson P. Force characteristics of nickel-titanium open-coil springs. Am J Orthod Dentofacial Orthop. 2010;138(2):142.e1-7

58. Steinbach G, Armstrong D Fau - Kharbanda OP, Kharbanda Op Fau - Petocz P, Petocz P Fau - Darendeliler MA, Darendeliler MA. An investigation of the forces used by clinicians to open spaces with coil springs. Aust Orthod J. 2006;22(2):115-20.

59. Lombardo L, Carlucci A, Palone MA-Ohoo, Mollica F, Siciliani G. Stiffness comparison of mushroom and straight SS and TMA lingual archwires. Prog Orthod. 2016;17(1):27.

60. Weltman B, Vig Kw Fau - Fields HW, Fields Hw Fau - Shanker S, Shanker S Fau - Kaizar EE, Kaizar EE. Root resorption associated with orthodontic tooth movement: a systematic review. Am J Orthod Dentofacial Orthop. 2010;137(4):462-76

Chapter 3 In Vitro Simulation of Forces and Moments Using Space Generation Mechanics with a Lingual Bracket System

3.1 Introduction

Lingual braces are a type of orthodontic appliance that can be used to resolve misaligned teeth by moving them into in a functional position. Lingual braces may have esthetic and social benefits for the patient as they reside on the inside of the teeth and are therefore less visible when compared to conventional orthodontic systems. As a result of this difference in bracket position, there are many differences in the biomechanics between lingual and labial bracket systems. The size and shape of the lingual arch form is different than the labial arch form[1].The anatomy of the lingual surfaces of the anterior teeth are concave, compared to the convex labial surface[2]. The distance between adjacent brackets (the inter-bracket distance) is larger for labial systems compared to lingual braces, which affects the length of free archwire between adjacent brackets[3]. The specific position of the brackets on a tooth affects the relationship of the applied forces to the center of resistance of the tooth, which affects the resultant forces and moments transmitted to the tooth support structure[1]. There is minimal research available with respect to the biomechanics of lingual braces systems in orthodontics; therefore, producing a quantitative understanding of this system allow for a better understanding of force and moment systems produced in treatment and lead to a better predictability of treatment outcomes.

It is critical to preserve the health of the teeth and surrounding tissues throughout orthodontic treatment. Large magnitude orthodontic forces and moments may produce undermining resorption, which can cause delayed tooth movement[4] and may increase the likelihood of root resorption[5]. Therefore, it is important that the forces and moments that orthodontic appliances exert on teeth are low enough in magnitude to avoid detrimental effects, while still generating the desired tooth movement.

Two shapes of archwires were used in this study: straight archwires and mushroom archwires. Straight archwires have no additional bends, while mushroom archwires are designed specifically for lingual orthodontic treatment and have specific bends that follow the anatomy of the inside of the dental arch where the lingual braces reside[6].

Two treatment types for generating space were used in this study: Nickel Titanium (NiTi) open coil springs and archwire stops. NiTi coil springs are initially compressed between teeth; the subsequent decompression of the coil creates space between the teeth to allow room to align crowded teeth. The archwire stop technique involves crimping orthodontic stops onto the orthodontic archwire, allowing an excess length of wire between teeth. This extra length of wire exerts the forces on the teeth to generate space to align the crowded teeth.

This study was designed to evaluate different wire types and treatment types using a lingual bracket system to generate space for a crowded dentition. The four experimental groups are as follows: 1. Straight archwires with NiTi coils, 2. Straight archwires with Stops, 3. Mushroom archwires with NiTi coils, 4. Mushroom archwires with stops. The goal of this study was to evaluate the differences between the four experimental groups to understand which systems may produce the most physiologic and clinically beneficial forces and moments on the teeth.

3.2 Materials and Methods

3.2.1 Orthodontic Simulator (OSIM)

Force and moment data were collected using the Orthodontic Simulator (OSIM); an in-vitro model of the human mouth to measure 3D forces and moments on each tooth around a dental arch (Fig 3.1) The OSIM was designed and validated at the University of Alberta[7] [8].

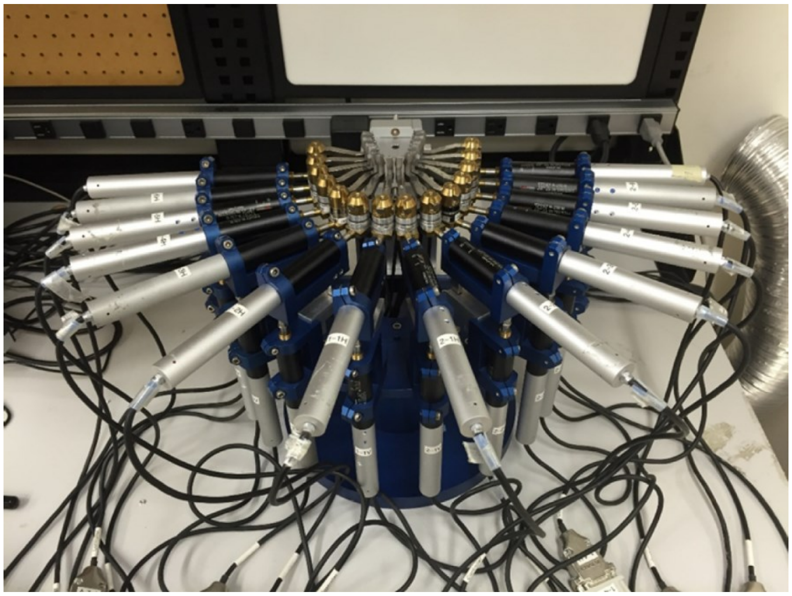
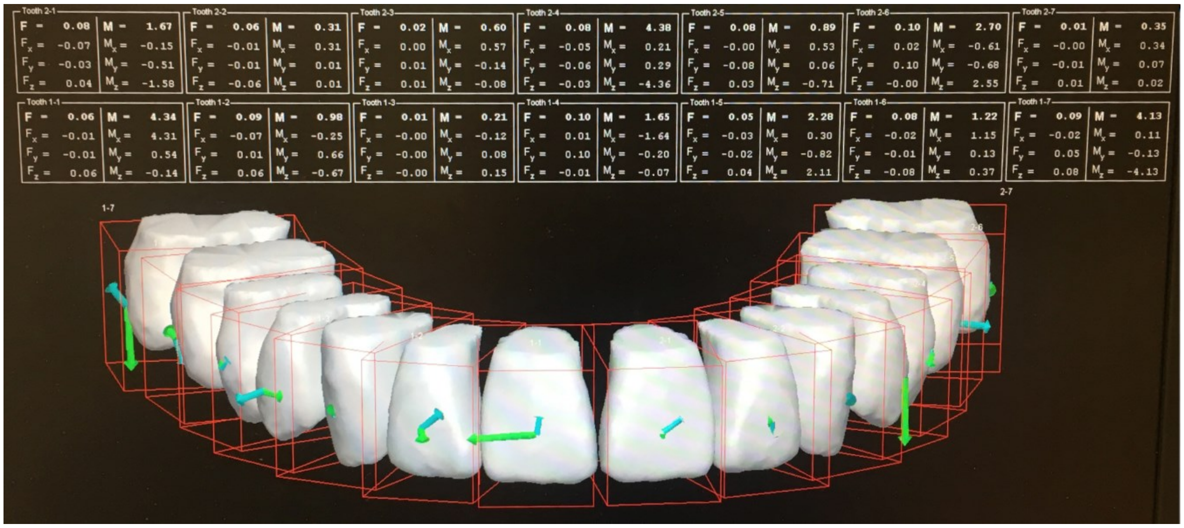


Figure 3.1 Orthodontic Simulator (OSIM)

The OSIM has stainless steel posts that are designed to represent the anatomic shape of teeth and are positioned in the shape of a dental arch. The metal teeth are rigidly attached to load cells (Nano17, ATI Industrial, Apex, NC, USA) which can measure the 3D forces and moments experienced by all of the teeth in the dental arch simultaneously. The load cells have a different coordinate system than the brackets, therefore a Jacobian transformation was used to transform the forces and moments measured at the load cells to the forces and moments experienced at the center of resistance of the teeth. A FARO arm (Faro Technologies, Lake Mary, Fla) was used to determine the position of the load cells and the brackets. The information from the FARO arm was used to transfer measurements from the load cell coordinate system and location to the bracket location and coordinate system for each tooth.

The force and moment data is then exported to computer software where it can be interpreted and analyzed. The MATLAB (MathWorks, Natick, Mass) computer software code written for in-house use provides a visual display of the forces and moments experienced by the teeth in real-time as the experiment is running (Fig. 3.2). This software also produces graphical representation of the data collected. The data files are then exported to complete statistical analysis.



Tooth 2-1
F = 0.08 M = 1.67
F_x = -0.07 M_x = -0.15
F_y = -0.03 M_y = -0.51
F_z = 0.04 M_z = -1.58

Tooth 2-2
F = 0.06 M = 0.31
F_x = -0.01 M_x = 0.31
F_y = -0.01 M_y = 0.01
F_z = -0.06 M_z = 0.01

Tooth 2-3
F = 0.02 M = 0.60
F_x = 0.00 M_x = 0.57
F_y = 0.01 M_y = -0.14
F_z = 0.01 M_z = -0.08

Tooth 2-4
F = 0.08 M = 4.38
F_x = -0.05 M_x = 0.21
F_y = -0.06 M_y = 0.29
F_z = -0.03 M_z = -4.36

Tooth 2-5
F = 0.08 M = 0.89
F_x = -0.00 M_x = 0.53
F_y = -0.08 M_y = 0.06
F_z = 0.03 M_z = -0.71

Tooth 2-6
F = 0.10 M = 2.70
F_x = 0.02 M_x = -0.61
F_y = 0.10 M_y = -0.68
F_z = -0.00 M_z = 2.55

Tooth 2-7
F = 0.01 M = 0.35
F_x = -0.00 M_x = 0.34
F_y = -0.01 M_y = 0.07
F_z = 0.01 M_z = 0.02

Tooth 1-1
F = 0.06 M = 4.34
F_x = -0.01 M_x = 4.31
F_y = -0.01 M_y = 0.54
F_z = 0.06 M_z = -0.14

Tooth 1-2
F = 0.09 M = 0.98
F_x = -0.07 M_x = -0.25
F_y = 0.01 M_y = 0.66
F_z = 0.06 M_z = -0.67

Tooth 1-3
F = 0.01 M = 0.21
F_x = -0.00 M_x = -0.12
F_y = -0.00 M_y = 0.08
F_z = -0.00 M_z = 0.15

Tooth 1-4
F = 0.10 M = 1.65
F_x = 0.01 M_x = -1.64
F_y = 0.10 M_y = -0.20
F_z = -0.01 M_z = -0.07

Tooth 1-5
F = 0.05 M = 2.28
F_x = -0.03 M_x = 0.30
F_y = -0.02 M_y = -0.82
F_z = 0.04 M_z = 2.11

Tooth 1-6
F = 0.08 M = 1.22
F_x = -0.02 M_x = 1.15
F_y = -0.01 M_y = 0.13
F_z = -0.08 M_z = 0.37

Tooth 1-7
F = 0.09 M = 4.13
F_x = -0.02 M_x = 0.11
F_y = 0.05 M_y = -0.13
F_z = 0.08 M_z = -4.13

Figure 3.2 Computer display of OSIM experiment

The metal teeth on the OSIM are positioned to represent a dental maxillary arch. A zeroing technique was used when the experimental archwires were ligated into the OSIM to ensure that the initial position was passive. Horizontal and vertical micrometers were adjusted so that each load cell had forces of less than 0.1N at the starting position. Once all of the teeth in the arch satisfied this criteria, this position was set as the zero position. Prior to each experiment, a bias of the load cells was completed prior to engaging the archwires or mechanics to facilitate zero forces and moments at the start of each experiment.

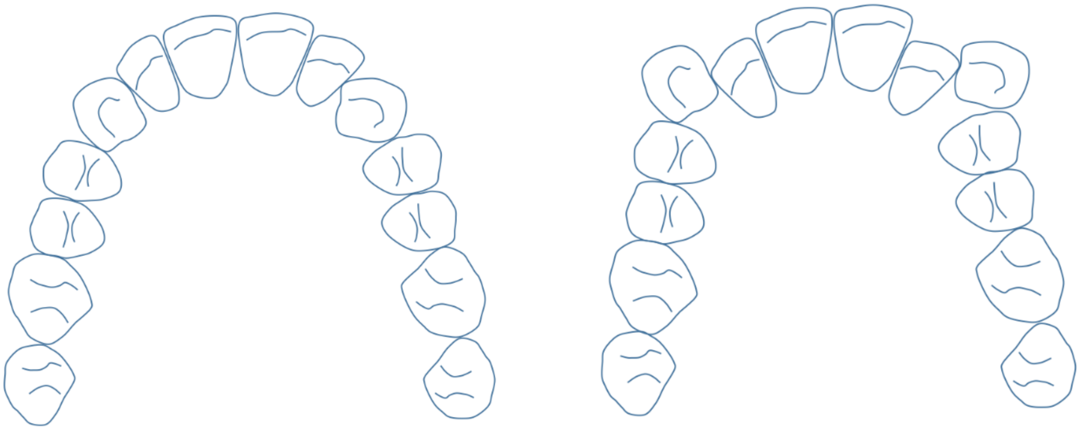
A temperature chamber surrounded the OSIM during experimental trials. The OSIM and the experimental materials were placed in the temperature chamber for one hour prior to experimental testing to reach 37°C. This was done to approximate the average temperature of the human oral cavity. This temperature setting is important to thermally activate the superelastic effect of the NiTi archwires[9].

3.2.2 Orthodontic Materials

Lingual self-ligating brackets (In-Ovation L, Dentsply GAC, York, PA, USA) with a slot size of 0.018x0.025 inches were placed on the lingual surface of the simulated maxillary dental arch including second molars. Liquid etchant (37% phosphoric acid, Reliance Ortho Prod. Inc.), metal primer (Reliance Ortho Prod. Inc.), bonding agent (OrthoSolo™, Ormco™), and composite resin (3M Unitek Transbond XT) were used to bond each bracket to the stainless steel anatomically designed posts on the OSIM. Two shapes of archwires were used: straight and mushroom. Both straight and mushroom archwires were 0.016” NiTi round wire (G&H Orthodontics®). All archwires used were from the same batch. Two treatment mechanics were used: NiTi open coils (0.010x0.030”, Ormco™) and stops (Medium 0.016-0.018, Speed System™). New archwires and treatment mechanics (coils and stops) were used for each experimental trial.

3.2.3 Experimental Set-up

The experimental set-up consisted of the teeth in the maxillary dental arch including right and left second molars. The right and left canines were moved out of the arch to simulate a crowded dentition. An example of a crowded dentition can be seen in Fig. 3.3.



a) *b)*

Figure 3.3 Illustrations of a maxillary dentition with and without crowded teeth

a) Well aligned maxillary dentition. b) Crowded maxillary dentition with insufficient space for the maxillary canines which are blocked out of the arch

All experiments started in an initial passive position. The different archwires and treatment mechanics were inserted into the brackets on the simulated teeth in this initial passive position.

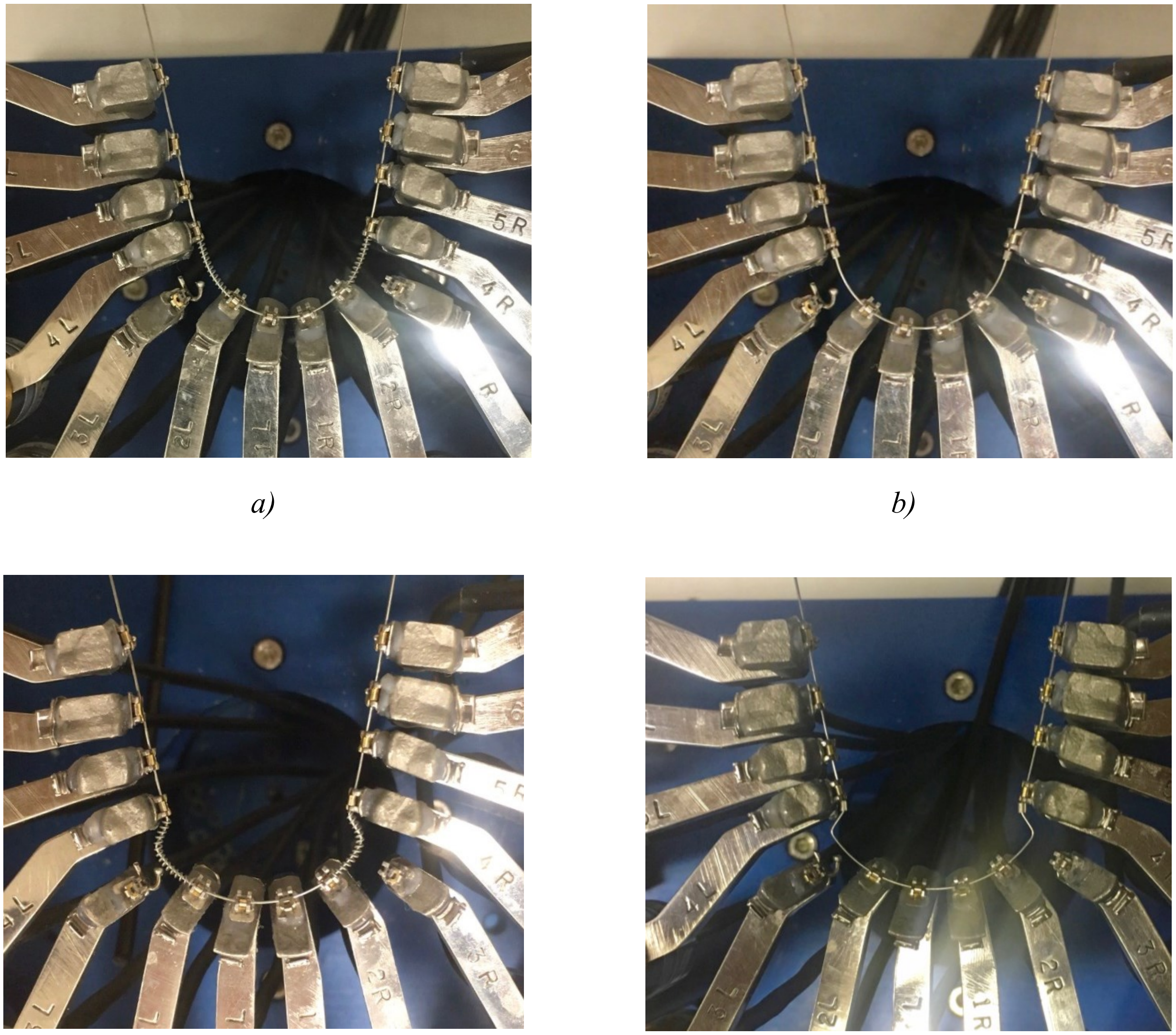
Four treatment groups were compared in this study (Fig. 3.4):

1. Straight archwires with NiTi coils

2. Straight archwires with stops

3. Mushroom archwires with NiTi coils

4. Mushroom archwires with stops



a)

b)

c)

d)

Figure 3.4 Experimental set-up positions on the OSIM

a) Straight archwire with coils, b) Straight archwire with stops, c) Mushroom archwire with coils, d) Mushroom archwire with stops

To begin an experiment, NiTi coils were measured and placed to passively fill the space between the lateral incisor and first premolar brackets on the OSIM. The length of the NiTi coils was 10mm for the straight archwires, and 12mm for the mushroom archwires. The mushroom archwires had a slightly increased coil length due to the extra length of wire in the mushroom bend. The stops were crimped onto the wire contacting the mesial aspect of the first premolar brackets bilaterally. The OSIM was first set-up and bonded for the straight archwires, and random assignment of NiTi coils and stops were tested. Next, the OSIM was set-up and bonded for the mushroom archwires, and random assignment of NiTi coils and stops were tested. For each experimental trial, new archwires and new treatment mechanics (coils and stops) were inserted into the OSIM. The same zero position was kept for both straight and mushroom archwires. Due to the different shape of the archwires, the anterior brackets were bonded differently for each wire to allow passive fit of each archwire. The shape of the mushroom wire allowed close adaptation of the bracket base to the anterior teeth. To maintain the same zero position for the straight wires, additional composite was added between the bracket base and the anterior teeth for the straight wire experiments.

The initial passive position allowed consistent placement of the specific wire and treatment type according to the group being tested. Once the OSIM was set up with the appropriate treatment group, an experimental trial could commence. To begin an experimental trial, the four anterior teeth (right and left central and lateral incisors) were moved lingually (inward) in 0.2mm increments to reach a total movement of 2.0mm to simulate a crowded dentition. This 2.0mm inward position will be referred to as the maximum crowded position. Therefore, the coils were compressed by 2.0mm and the stops compressed the archwire by 2.0mm bilaterally as the teeth were moved lingually into the maximum crowded position. Force and moment data on all teeth in the arch (except the canines) were collected by the OSIM at each 0.2mm increment. At each increment, the load cell records 50 readings over approximately 1 second and the average of these readings are reported.

3.2.4 Force and Moment Measurements

Forces and moments on the OSIM were measured on all teeth in the single maxillary dental arch simultaneously. Each force and moment measurement was made along x, y, and z axes (Fig. 3.5). Forces in the x-direction represent mesial-distal forces, forces in the y-direction represent buccal-lingual forces, and forces in the z- direction represent vertical occlusal-gingival forces. Moments in the x-direction represent buccal-lingual crown/root torque, moments in the y-direction represent mesial-distal tipping, and moments in the z-direction represent rotational movements. Therefore, F_x, F_y, F_z forces and M_x, M_y, M_z moments were recorded for each tooth.

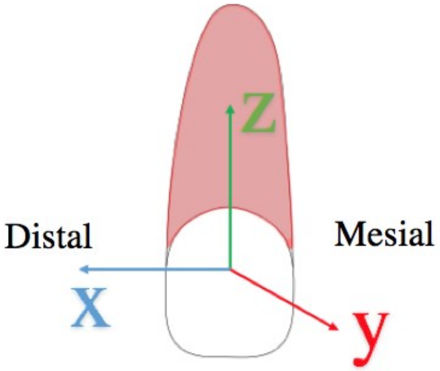


Figure 3.5 Representative coordinate system for a single simulated tooth on OSIM

As a result of the coordinate system on the OSIM, the direction of the x axis on individual teeth varies along the arch. Therefore, the positive direction for F_x, M_y, and M_z also varies along the arch in relation to their anatomical direction. The y and z axes are in the same direction for each tooth along the arch. During data analysis, the force and moment data were adjusted to compare the same anatomical direction of tooth movement for each tooth in the arch. Therefore, the force and moment data will be discussed in terms of the clinical tooth movement directions. Data values were anatomically adjusted to allow averaging of right and left sides of the OSIM.

3.2.5 Sample Size Calculation

A pilot study was completed which consisted of ten trials for each of the four experimental groups. The results from the pilot study were used to determine the sample size for the full trial. Detection of forces of >0.2N and Moments of >3Nmm was used; relevant forces and moments for tooth movement from previous literature[10 11]. A power of $1\text{-}\beta = 0.90$ and $\alpha = 0.05$ were used. The following forces and moments were used: maxillary lateral incisors: F_y, M_x and maxillary first premolars: F_x, M_y. The following sample size calculation formulas were used[12]:

Sample size: $n = \frac{\lambda}{\Delta}$

When $1\text{-}\beta = 0.90$ and $\alpha = 0.05$; $\lambda = 14.18$

$\Delta = \frac{1}{\sigma^2}\sum_{i=1}^{k}(\mu_i - \bar{\mu})^2$, $\bar{\mu} = \frac{1}{k}\sum_{j=1}^{k}\mu_j$

The result was a sample size of 44 trials per each of the four experimental groups.

3.2.6 Statistical Analysis

The statistical analysis was performed using version 23 IBM® SPSS® Statistics 64-bit edition. A significance level of α=0.05 was chosen for all statistical analyses. Analysis of the full trial data examines the forces and moments experienced by the maxillary first premolars (tooth #1.4 and tooth #2.4) and maxillary lateral incisors (tooth #1.2 and tooth #2.2) at the maximum crowded position (the 2.0mm inward position on the OSIM) at the center of resistance of the tooth. The rationale for exploring these specific teeth is because they are located closest to where we applied the treatment mechanics. Specifically, forces in the x-direction, forces in the y-direction, and moments in the x, y, and z directions; F_x, F_y, M_x, M_y, and M_z respectively. Forces in the z-direction (F_z) were not included in the analysis because they refer to intrusion and extrusion forces which were not considered to be the main forces of interest in this study. From previous literature[10,11], the amount of force to create tooth movement is >0.2N, and the amount of moment to create tooth movement is >3Nmm.

Repeated measures mixed multivariate analysis of variance (MANOVA) was used to determine if there are differences in the forces or moments of interest experienced by the maxillary first premolars and maxillary lateral incisors between the two different treatments (coils and stops) and the two different archwires (straight archwires and mushroom archwires) at the maximum crowded position. The model assumptions for MANOVA were tested: normality was assessed using boxplots, equal covariance-variance matrices were assessed using Box's M-Test, and linearity was assessed using scatterplot matrices. Multicollinearity was assessed using Pearson correlation coefficients between dependent variables. Some values were >0.9, therefore multicollinearity may be present and must be taken into consideration when interpreting the results. However, because these data have multiple continuous dependent variables, MANOVA was chosen as the most appropriate statistical analysis. Univariate outliers were assessed visually using boxplots and multivariate outliers were assessed using Mahalanobis distance. Both univariate and multivariate outliers were present, therefore the statistical analysis was completed with and without the outliers included. The statistical significance was unaffected by both univariate and multivariate outliers, therefore the analysis reported includes all data values.

Average values of right and left sides of the OSIM arch were used for the analysis. Due to the right hand coordinate system, data values were anatomically adjusted to allow averaging of right and left sides of the OSIM. One trial from the straight archwire stops group was excluded due to one of the stops becoming loose during the experimental trial.

3.3 Hypotheses

Maxillary First Premolars:

H_{o1}: There is no interaction between **the wire type and treatment type on** mean F_x, F_y, M_x, M_y, M_z of maxillary first premolars at the maximum crowded position

H_{o2}: There is no difference between **the treatment types** in relation to mean F_x, F_y, M_x, M_y, M_z of maxillary first premolars at the maximum crowded position

H_{o3}: There is no difference between the **wire types** in relation to mean F_x, F_y, M_x, M_y, M_z of maxillary first premolars at the maximum crowded position

H_{a1}: There is an interaction between the **wire type and treatment type** on mean F_x, F_y, M_x, M_y, M_z of maxillary first premolars at the maximum crowded position

H_{a2}: There is a difference between the **treatment types** in relation to mean F_x, F_y, M_x, M_y, M_z of maxillary first premolars at the maximum crowded position

H_{a3}: There is a difference between the **wire types** in relation to mean F_x, F_y, M_x, M_y, M_z of maxillary first premolars at the maximum crowded position

Maxillary Lateral Incisors:

H_{o1}: There is no interaction between **the wire type and treatment type on** mean F_x, F_y, M_x, M_y, M_z of maxillary lateral incisors at the maximum crowded position

H_{o2}: There is no difference between **the treatment types** in relation to mean F_x, F_y, M_x, M_y, M_z of maxillary lateral incisors at the maximum crowded position

H_{o3}: There is no difference between the **wire types** in relation to mean F_x, F_y, M_x, M_y, M_z of maxillary lateral incisors at the maximum crowded position

H_{a1}: There is an interaction between the **wire type and treatment type** on mean F_x, F_y, M_x, M_y, M_z of maxillary lateral incisors at the maximum crowded position

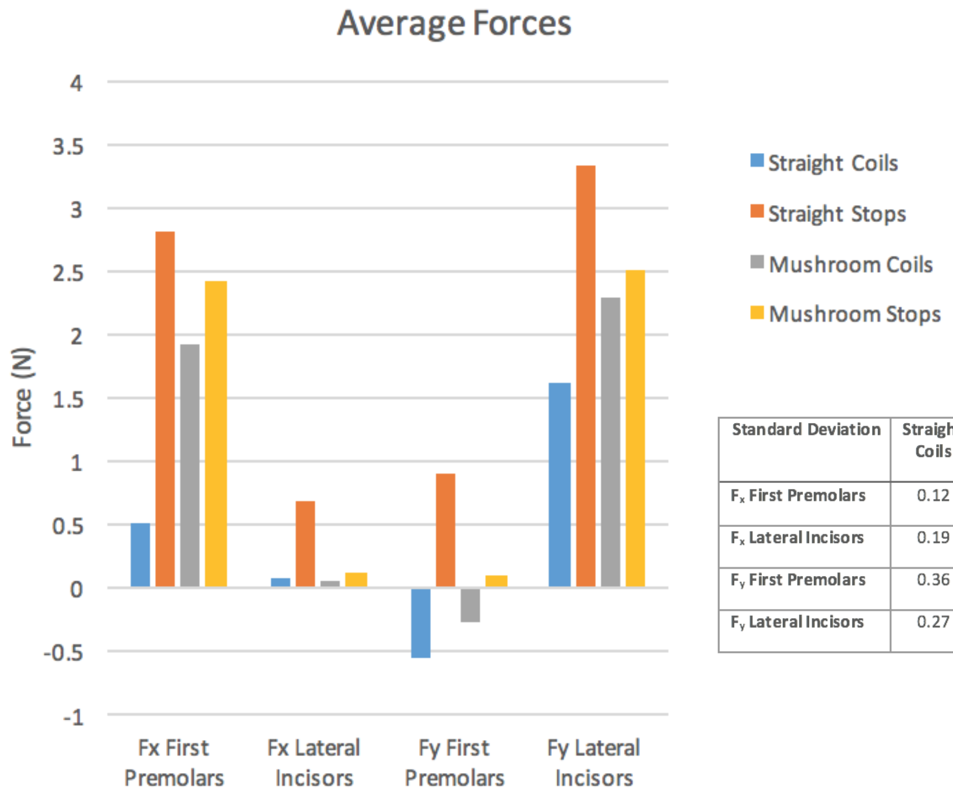
H_{a2}: There is a difference between the **treatment types** in relation to mean F_x, F_y, M_x, M_y, M_z of maxillary lateral incisors at the maximum crowded position

H_{a3}: There is a difference between the **wire types** in relation to mean F_x, F_y, M_x, M_y, M_z of maxillary lateral incisors at the maximum crowded position

3.4 Results

3.4.1 Comparison of Average Force and Moments

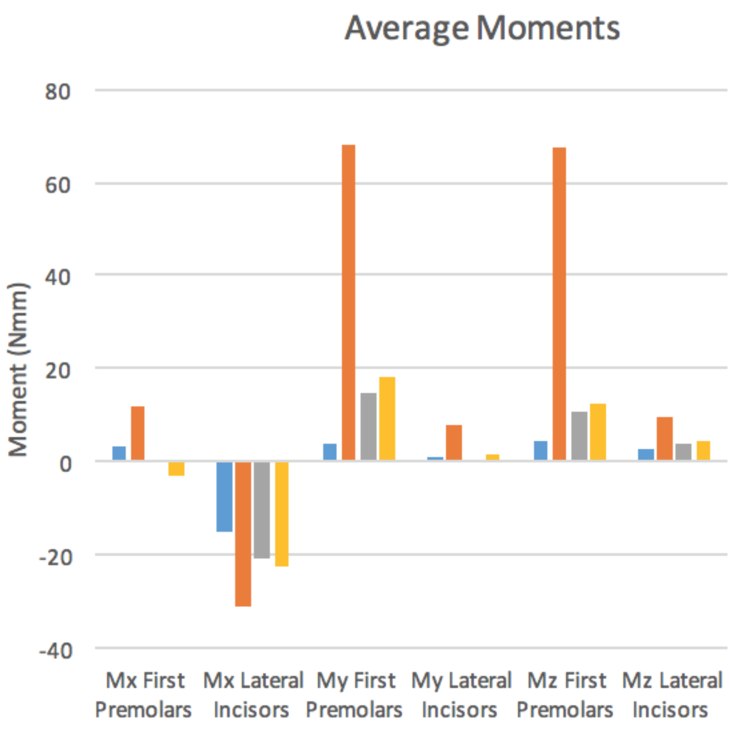
A comparison of the average forces and moments experienced by the lateral incisors and first premolars can be seen in Fig. 3.6 and Fig 3.7. Due to the coordinate system used on the OSIM, the positive and negative values represent the direction of the force or moment with respect to the coordinate system shown in Fig. 3.5. Comparison of the average forces for all four treatment groups are seen in Fig. 3.6. The positive F_x direction for the first premolars and lateral incisors represents distal movement. All four treatment groups showed positive F_x values for the first premolars above the threshold for tooth movement (>0.2N). F_x values for the lateral incisors were all below the clinically relevant 0.2N, except for the straight wire stops group. The positive F_y values represent labial/lingual movements, and negative F_y values represent lingual movement. The F_y values for the first premolars showed a different direction when comparing coils and stops; both coils treatment groups had negative F_y values (lingual direction), where both stops groups showed positive F_y values (buccal direction). The F_y values of the lateral incisors for all treatment groups were >0.2N and in the labial direction.



Standard Deviation	Straight Coils	Straight Stops	Mushroom Coils	Mushroom Stops
F_x First Premolars	0.12	1.36	0.44	0.18
F_x Lateral Incisors	0.19	0.40	0.16	0.17
F_y First Premolars	0.36	1.09	0.23	0.28
F_y Lateral Incisors	0.27	0.47	0.28	0.20

Figure 3.6 Average forces between the experimental groups

Average moments between the four treatment groups are shown in Fig. 3.7. The threshold for clinical tooth movement are moments >3Nmm. The positive M_x is lingual crown torque, and negative M_x is buccal crown torque. Positive My value is distal crown tip, negative M_y is mesial crown tip. Positive M_z value is mesial-buccal rotation, negative M_z value is distal-buccal rotation. The straight stops group had the highest moment values in every direction. Straight coils had the lowest moment values in every direction. The mushroom wire groups had fairly similar moment values despite which treatment group was used.



Standard Deviation	Straight Coils	Straight Stops	Mushroom Coils	Mushroom Stops
M_x First Premolars	2.34	15.86	2.18	2.24
M_x Lateral Incisors	2.33	4.35	2.85	1.34
M_y First Premolars	0.97	47.12	3.96	2.18
M_y Lateral Incisors	2.15	4.30	2.35	2.53
M_z First Premolars	1.10	70.31	4.54	5.80
M_z Lateral Incisors	3.04	4.73	3.95	4.44

Figure 3.7 Average moments between the experimental groups

3.4.2 Anterior Force Comparisons

The average combined anterior force of the central incisors and lateral incisors can be seen in Fig. 3.10. The combined anterior force $F_{a(total)}$ was the sum of the anterior resultant force of the F_x and F_y forces measured on the central incisors and lateral incisors (Fig. 3.8).

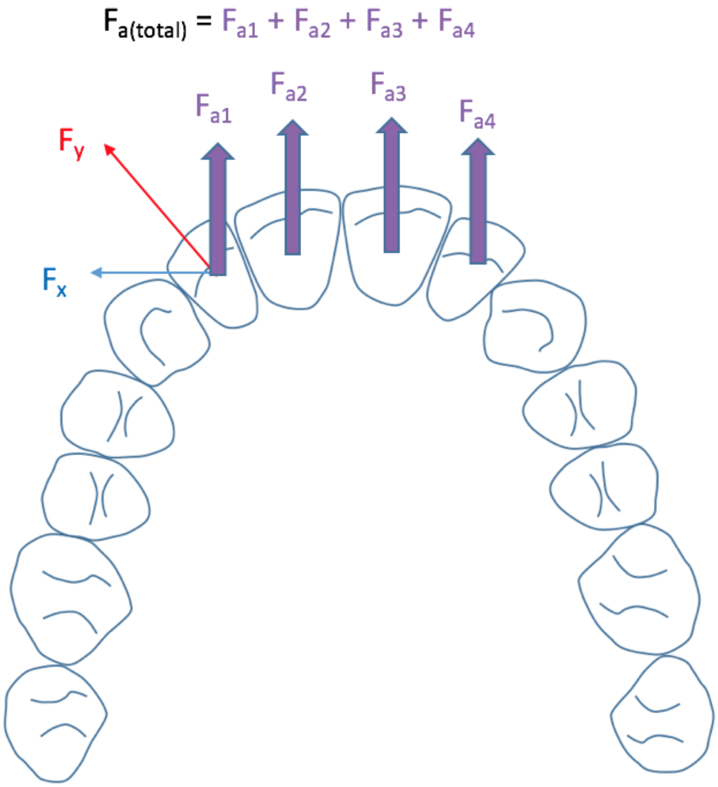


Figure 3.8 Sum of the total anterior force of the four anterior teeth

The equation used to calculate the resultant force can be seen in Fig. 3.9. The angle of the OSIM micrometers for the central incisors and lateral incisors was 11 degrees and 35 degrees, respectively. Therefore, the following equations were used to calculate F_a:

$$F_{a(central\ incisors)} = F_y(\cos(11))$$

$$F_{a(lateral\ incisors)} = F_y(\cos(35))$$

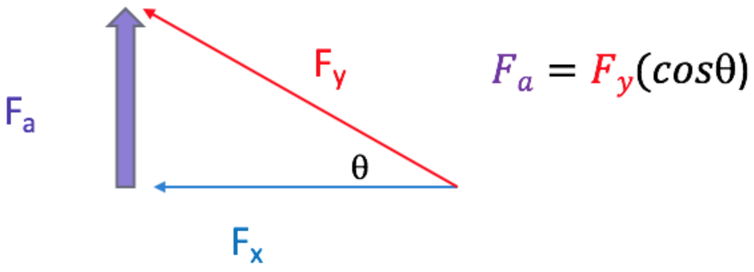


Figure 3.9 Calculation of Fa values

The comparison of the average total anterior force between the four experimental groups can be seen in Fig. 3.10. The straight stops group showed the highest total anterior force, while the straight coils showed the lowest total anterior force. Mushroom archwires showed similar average anterior force values despite which treatment type was used.

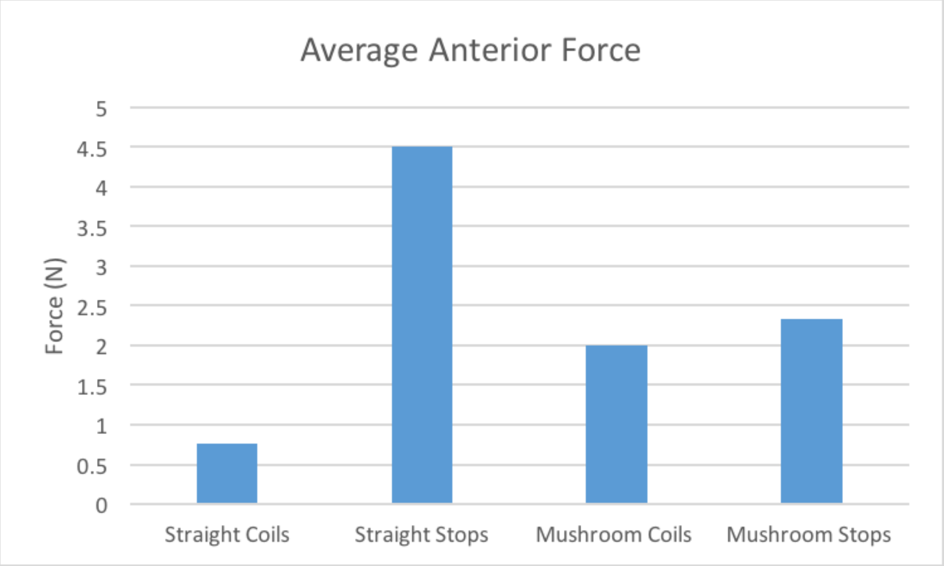


Figure 3.10 Average total anterior force between groups

3.4.3 Comparing Treatment Mechanics

The results presented in Table 3.1 show the values for the wire types when comparing the different treatment mechanics. Many of the forces and moments show statistically significance with p-values <0.05; the magnitude of the differences can be seen in Table 3.1.

Table 3.1 Univariate pairwise comparisons at the maximum crowded position of first premolars and lateral incisors for wire type when using different treatments

Outcome Measurement	Wire	Tooth	Treatment (A)	Treatment (B)	Mean Difference (A-B)	p-value	95% Confidence Interval
F_x (N)	Straight	First premolars	Stops	Coils	2.29	<0.001	[2.09, 2.48]
	Straight	Lateral Incisors	Stops	Coils	0.61	<0.001	[0.55, 0.67]
	Mushroom	First premolars	Stops	Coils	0.52	<0.001	[0.32, 0.71]
	Mushroom	Lateral Incisors	Stops	Coils	0.08	0.013	[0.02, 0.14]
F_y (N)	Straight	First premolars	Stops	Coils	1.45	<0.001	[1.24, 1.66]
	Straight	Lateral Incisors	Stops	Coils	1.71	<0.001	[1.61, 1.82]
	Mushroom	First premolars	Stops	Coils	0.36	0.001	[0.16, 0.57]
	Mushroom	Lateral Incisors	Stops	Coils	0.21	<0.001	[0.10, 0.31]
M_x (Nmm)	Straight	First premolars	Stops	Coils	8.50	<0.001	[6.23, 10.77]
	Straight	Lateral Incisors	Stops	Coils	-16.44	<0.001	[-17.46, -15.42]
	Mushroom	First premolars	Stops	Coils	-2.98	0.010	[-5.24, -0.72]
	Mushroom	Lateral Incisors	Stops	Coils	-1.76	0.001	[-2.77, -0.74]
M_y (Nmm)	Straight	First premolars	Stops	Coils	63.94	<0.001	[55.89, 72.00]
	Straight	Lateral Incisors	Stops	Coils	6.86	<0.001	[6.19, 7.52]
	Mushroom	First premolars	Stops	Coils	3.58	0.379	[-4.43, 11.58]
	Mushroom	Lateral Incisors	Stops	Coils	0.98	0.004	[0.32, 1.65]
M_z (Nmm)	Straight	First premolars	Stops	Coils	63.32	<0.001	[54.05, 72.59]
	Straight	Lateral Incisors	Stops	Coils	6.92	<0.001	[6.36, 7.49]
	Mushroom	First premolars	Stops	Coils	1.70	0.716	[-7.52, 10.92]
	Mushroom	Lateral Incisors	Stops	Coils	0.88	0.002	[0.32, 1.45]

When using stops treatment mechanics, the maxillary first premolars experience increased mean F_x (mesial-distal), F_y (buccal-lingual), M_y (mesial-distal root tip), and M_z (rotation) values compared to coils treatment mechanics despite which wire type was used. For the maxillary first premolars, when using straight archwires, the stops had increased mean M_x

(crown torque) values compared to coils, but when using mushroom archwires, the stops had decreased mean M_x values compared to coils.

When using stops treatment mechanics, the maxillary lateral incisors experienced increased mean F_x, F_y, M_y, and M_z values compared to coils treatment mechanics despite which wire type was used at the maximum crowded position. For the maxillary lateral incisors, the stops mechanics had decreased mean M_x values for both wire types.

The straight wire stops group had generally larger forces and moments compared to the other groups. When comparing treatment types, the largest magnitude of differences between stops and coils was for M_y and M_z values of maxillary first premolars when using straight archwires (Table 3.1).

3.4.4 Comparing Wire Types

The results presented in Table 3.2 show the values for the treatment types when comparing the different wire types. Many of the forces and moments show statistically significance with p-values <0.05; the magnitude of the differences can be seen in Table 3.2. Clinically significant values [10] [11] are highlighted in Table 3.2.

When using mushroom archwires, the maxillary first premolars experienced increased mean F_x, F_y, M_y, M_z values compared to straight archwires when coils mechanics were used, whereas the mushroom archwires had decreased mean F_x, F_y, M_y, M_z values compared to straight archwires when stops mechanics were used. The maxillary first premolars had decreased mean M_x values with mushroom compared to straight archwires for both treatment types.

Table 3.2 Univariate pairwise comparisons at the maximum crowded position of first premolars and lateral incisors for treatment type when using different archwires

Outcome Measurement	Treatment	Tooth	Wire (A)	Wire (B)	Mean Difference (A-B)	p-value	95% Confidence Interval
F_x (N)	Coils	First Premolars	Mushroom	Straight	1.39	<0.001	[1.20, 1.59]
	Coils	Lateral Incisors	Mushroom	Straight	-0.02	0.519	[-0.04, 0.08]
	Stops	First Premolars	Mushroom	Straight	-0.38	<0.001	[-0.57, -0.18]
	Stops	Lateral Incisors	Mushroom	Straight	-0.55	<0.001	[-0.61, -0.49]
F_y (N)	Coils	First Premolars	Mushroom	Straight	0.29	0.006	[0.09, 0.50]
	Coils	Lateral Incisors	Mushroom	Straight	0.69	<0.001	[0.59, 0.79]
	Stops	First Premolars	Mushroom	Straight	-0.80	<0.001	[-1.00, -0.59]
	Stops	Lateral Incisors	Mushroom	Straight	-0.82	<0.001	[-0.92, -0.72]
M_x (Nmm)	Coils	First Premolars	Mushroom	Straight	-3.22	0.005	[-5.48, -0.97]
	Coils	Lateral Incisors	Mushroom	Straight	-5.79	<0.001	[-6.80, -4.77]
	Stops	First Premolars	Mushroom	Straight	-14.70	<0.001	[-16.98, -12.43]
	Stops	Lateral Incisors	Mushroom	Straight	8.90	<0.001	[7.88, 9.92]
M_y (Nmm)	Coils	First Premolars	Mushroom	Straight	10.96	0.008	[2.95, 18.96]
	Coils	Lateral Incisors	Mushroom	Straight	-0.51	0.134	[-1.17, 0.16]
	Stops	First Premolars	Mushroom	Straight	-49.41	<0.001	[-57.46, -41.36]
	Stops	Lateral Incisors	Mushroom	Straight	-6.38	<0.001	[-7.04, -5.71]
M_z (Nmm)	Coils	First Premolars	Mushroom	Straight	6.69	0.154	[-2.53, 15.91]
	Coils	Lateral Incisors	Mushroom	Straight	0.79	0.006	[0.23, 1.35]
	Stops	First Premolars	Mushroom	Straight	-54.92	<0.001	[-64.20, -45.65]
	Stops	Lateral Incisors	Mushroom	Straight	-5.25	<0.001	[-5.81, -4.68]

When using straight archwires, the maxillary lateral incisors experienced increased mean F_x and M_y values with both coils and stops compared to the mushroom archwires. The maxillary lateral incisors experienced increased mean F_y and M_z values with mushroom archwires compared to straight archwires when coils mechanics were used, whereas the mushroom archwires had decreased mean F_y and M_z values compared to straight archwires when stops mechanics were used. When using mushroom archwires, the maxillary lateral incisors had decreased mean M_x values with coils and increased mean M_x values when using stops compared to the straight archwires.

When comparing wire types, the largest magnitude of differences between mushroom archwires and straight archwires was again for M_y and M_z values of maxillary first premolars (Table 3.2)

3.5 Discussion

3.5.1 Discussion of overall trends

Three general observations were noticed in the analysis: 1. Mushroom archwires had similar mean force and moment values despite which treatment type is used, 2. Coils mechanics had similar mean force and moment values despite which archwire type was used, 3. Both archwire types had greater mean force and moment values when using stops compared to coils. These three observations may be useful for applications in clinical orthodontics when considering which treatment mechanics and archwire types to use for patients. For example, observation #1 suggests that mushroom archwires may provide similar clinical tooth movements despite which treatment type was chosen. This may be due to the additional bend the mushroom archwires have adjacent to the first premolars (Fig. 3.4). This additional bend in the mushroom archwires appears to provide similar effects to a stop as it is located against the mesial surface of the first premolar bracket. This additional bend in the mushroom archwires also allows closer adaptation of the wire to the teeth because the wire shape is closer to the anatomical shape of the lingual dental arch.

Observation #2 and #3 suggest that clinically there may be greater tipping, rotational, mesial-distal, and buccal-lingual tooth movements when using stops compared to coils. This observation could be seen because the stops are rigidly fixed onto the archwire and therefore prevents the wire from sliding and has more side effects on the adjacent tooth. These results could be beneficial or unfavourable depending on the direction the tooth needs to be moved. For example, if there is a clinical case with a crowded dentition and mesially tipped first premolars, the side effects of the stops mechanics may be beneficial because they produce more distal tipping which would move the tooth in a desired direction in that specific case. In comparison, the coils sit on top of the archwire and still allow the archwire to slide. Therefore, if there is a clinical case with crowding and normally positioned first premolars, the coils treatment mechanics may produce less side effects on the first premolars.

The results from this statistical analysis may be important for clinical orthodontic treatment because understanding the differences noted between treatment type and wire types may help us make decisions on which treatment options will be the most beneficial for patients.

3.5.2 Comparisons Between Treatment Groups

The F_y values for the first premolars showed a different direction when comparing coils and stops. The coils group showed lingual movement, and the stops group showed buccal movement. This difference in direction could be due to a different line of action of the force in the buccal-lingual direction resulting from the position of the coils. The stops are placed directly in line with the first premolar brackets, where the coils become directed at an angle to the bracket when compressed. This is an interesting observation to keep in mind when planning treatment mechanics. Based on the observations in this study, in a similar clinical situation, the desired tooth movements of the first premolars may influence the decision to choose stops or coils mechanics.

The groups using mushroom wires showed similar forces and moments despite which treatment mechanics were used. Therefore, based on the observations of this study, if a clinician is using mushroom wires clinically, the choice between coils or stops mechanics will result in similar movements on the first premolars and lateral incisors.

The straight archwire stops group showed the highest magnitudes for all of the forces and moments reported. As discussed above, this treatment group showed a unique pattern of results due to a threshold that was reached in approximately half of the trials. When this threshold was reached, the wire appeared to temporarily buckle out of the original plane, and then moved back into the original plane again. This buckling effect caused an unpredictable amount of force and moment values to be experienced by the first premolars and lateral incisors.

In all treatment groups the first premolars experienced clinically significant distal movement (F_x). This would be expected because both treatment mechanics were located adjacent to the first premolars, creating a force pushing distal on the posterior teeth. The lateral incisors experienced clinically insignificant F_x values except for the straight archwire stops group. In the straight archwires stops group, the lateral incisors had clinically significant distal movement. The expected result would have been mesial movement of the lateral incisors. As will be discussed further in Section 3.5.3, this result may be due to the unique out-of-plane buckling effect of the wire in the straight archwire stops group. The magnitude of the F_x values were larger on the first premolars than on the lateral incisors. For the groups using stops mechanics, this likely occurs because the stops mechanics are located immediately adjacent to the first premolar brackets. For the groups using coils mechanics, the reasoning is less clear. This result could be due to direction the coils push on the lateral incisors as the coils are compressed, resulting in a direction of force that is expressed more as buccal movement (higher F_y values) than mesial-distal movement (lower F_x) values.

The anterior force comparisons shown in Figure 3.10 show the magnitude of the sum of the anterior force on the four incisors. If we assume that 0.2N is the minimum force required to move a single tooth, forces above 0.8N would be required to move the four incisors. The only group that was not above this threshold was the straight coils group. This could be because the coils in this study were only activated by 2mm, which may be less than coils would be activated clinically. A previous in-vitro study by Brauchli et al.[13]looked at the compression of different orthodontic NiTi coil springs when they were compressed at 25% of their original length. For the coils we used in our study, Brauchli et al. found that the average force at 25% compression was 0.45N with standard deviation of 0.02N[13]. In our study, the NiTi coil springs were compressed approximately 17-20% of their original length. The force values measured in this study were slightly less than the 0.45N reported by Brauchi et al.[13], which would be the approximate magnitude expected because the NiTi coils were compressed slightly less. According to the manufacturer's instructions, the amount of clinical compression of the NiTi coil springs should be approximately 1.3-1.4 times the bracket length. Therefore, in this study the coils were likely compressed slightly less than they would be clinically. However, one of the advantages of this in-vitro study is that it allows a reproducible experimental set-up to compare the treatment groups. Therefore, to achieve this reproducible experimental setting to compare the four treatment groups, the coils were started in an initial passive position, and then compressed 2mm. Clinically, we would not expect the coils to return to a completely passive position, because the force they would be exerting on the teeth at that point would be less than the threshold for tooth movement. This may explain why the total anterior force of the four incisors for the straight archwire coils group in this study was less than we would expect clinically.

3.5.3 Straight Archwire Stops Data

In approximately half of the trials in this data set there was a unique pattern of forces and moments on the maxillary first premolars; either unilaterally or bilaterally (22 trials showed this trend; 21 trials did not). Near the maximum crowded position this unique pattern consisted of F_x values that decreased abruptly and then increased again, and M_y and M_z values would increase greatly. The F_y and M_x values for the straight stops data also had much greater magnitude than the other experimental groups. An example of this type of response can be found in the Appendix (Fig. 2.1). It appears that at this threshold point, the wire would buckle out of the occlusal plane (temporarily increasing the values in another plane), and then move back into the original plane again. When the wire returned back to its original plane, the F_x values became consistent again.

This data suggests that when placing stops on a straight archwire, there may be a certain threshold of force or deformation which causes the archwire to buckle out of its original plane, causing different forces and moments to be experienced by the teeth compared to if all deformation were in the desired occlusal plane. It may be unpredictable in which direction or plane the archwire may buckle, and this may occur unilaterally, bilaterally, or not at all. In the in-vitro study design, the stops were secured on the archwire with the same amount of activation on both sides in the neutral position. Despite the controlled conditions of this in-vitro study design, approximately half the trials exhibited this out-of-plane buckling effect, either unilaterally or bilaterally. Clinically these movements may be of interest when planning treatment mechanics using stops with straight archwires. The results from this study suggest that larger deformation of the straight archwires when using stops mechanics may lead to an unpredictable buckling effect of the wire. We may expect all of the other experimental groups to reach this type of threshold eventually given enough prescribed deformation of the archwire. However, for the remaining three experimental groups, no out-of-plane archwire buckling effect was seen. This would indicate that the straight archwire with stop mechanics is less predictable than the other simulated treatment types considered in this study when considering the proposed out-of-plane buckling response.

3.5.4 Clinical Significance

When comparing the different archwire types and treatment types, many of the forces and moments had clinically relevant values for initiating tooth movement; forces >0.2N and moments >3Nmm[10,11]. These reported thresholds were chosen because they have been generally accepted by the orthodontic literature as the thresholds for inducing tooth movement, albeit the level of evidence to support them is low. There were differences in magnitude and direction of the forces and moments between the different archwire types and treatment types in this study. Therefore, the differences observed between the experimental groups may be of clinical interest when planning treatment mechanics.

Although the force and moment values in this study reached levels of clinical tooth movement, there are no values in the literature to indicate the magnitude of forces or moments that would be too large and potentially cause damage to the teeth and surrounding tissues for this particular scenario. There are guidelines in the literature to suggest magnitudes of forces that may be detrimental to the teeth and surrounding tissues,[14] however, the overall evidence for these values is low. The optimal force levels for tooth movement are based on expert opinion rather than well designed studies. It is generally accepted that lighter forces are more beneficial for tooth movement, however there has to be enough force generated to allow the tooth to move. If a force or moment applied to a tooth is greater than the threshold for tooth movement, we would expect to see clinical tooth movement. The tooth would not necessarily move faster or have an increased magnitude of movement with increased force levels above this threshold. The most desirable force or moment values produced by a treatment group may occur when the standard deviation of the values are all above the threshold for tooth movement, and less than the amount that may cause harmful side effects to the tooth and surrounding tissues. This would allow the clinician to have confidence that the clinical tooth movement would occur as planned, while avoiding any negative side effects.

Considering the information we have about optimal forces for tooth movement, it would be interesting to consider a clinically acceptable maximum threshold that would avoid damage to the biologic structures. There is currently no evidence based value to describe a maximum force threshold. If based on expert opinion, Proffit et al.[14] suggest that 120g may be the high end of the optimal force range (which would be approximately 1.2N). The standard deviation of the measured values in the straight stops group was above this 1.2N maximum threshold for F_x. Therefore, because some of the experimental trials in the straight stops exceeded 1.2N, this archwire and mechanics combination may be more likely to cause harmful side effects to the biologic structures if activated near the 2.0mm per side in this study. It must also be kept in mind that this experimental group showed buckling of the archwire in approximately half of the trials. Perhaps if the archwire is activated enough to cause it to buckle, the increased forces from the unpredictable effects of the buckling may exceed this 1.2N value.

3.6 Conclusion

The results from this statistical analysis showed that there were differences in the mean forces and moments of interest (F_x, F_y, M_x, M_y) experienced by the teeth of interest (maxillary first premolars and maxillary lateral incisors) between the two different treatments (coils and stops) and the two different archwires (straight archwires and mushroom archwires) at the maximum crowded position. Many of the force values were above 0.2N, and many of the moment values were above 3Nmm, which is the threshold for clinical tooth movement as determined by previous literature[10,11]. Therefore, this analysis provided interesting observations that may have applications in clinical orthodontic treatment.

References:

1. George RD, Hirani S. Fully-customized lingual appliances: how lingual orthodontics became a viable treatment option. J Orthod. 2013;40 Suppl 1:S8-13.

2. Shpack N, Geron S, Floris I, Davidovitch M, Brosh T, Vardimon AD. Bracket Placement in Lingual vs Labial Systems and Direct vs Indirect Bonding. The Angle Orthodontist 2007;77:509-517.

3. Lombardo L, Wierusz W Fau - Toscano D, Toscano D Fau - Lapenta R, Lapenta R Fau - Kaplan A, Kaplan A Fau - Siciliani G, Siciliani G. Frictional resistance exerted by different lingual and labial brackets: an in vitro study. Prog Orthod. 2013;14:37

4. Kitaura H, Kimura K, Ishida M, Sugisawa H, Kohara H, Yoshimatsu M et al. Effect of Cytokines on Osteoclast Formation and Bone Resorption during Mechanical Force Loading of the Periodontal Membrane. Scientific World Journal. 2014;2014:617032

5. Weltman B, Vig Kw Fau - Fields HW, Fields Hw Fau - Shanker S, Shanker S Fau - Kaizar EE, Kaizar EE. Root resorption associated with orthodontic tooth movement: a systematic review. Am J Orthod Dentofacial Orthop. 2010;137(4):462-76.

6. Fujita K. New orthodontic treatment with lingual bracket mushroom arch wire appliance.

7. Badawi H. The use of multi-axis force transducers for orthodontic force and moment identification. Edmonton, AB, Canada: University of Alberta 2009. [thesis]

8. Badawi HM, Toogood RW, Carey JPR, Heo G, Major PW. Three-dimensional orthodontic force measurements. American Journal of Orthodontics and Dentofacial Orthopedics 2009;136:518-528.

9. Lombardo L, Marafioti M Fau - Stefanoni F, Stefanoni F Fau - Mollica F, Mollica F Fau - Siciliani G, Siciliani G. Load deflection characteristics and force level of nickel titanium initial archwires. Angle Orthod. 2012;82(3):507-21

10. Nanda R. Biomechanics in Clinical Orthodontics Philadelphia: WB Saunders Co; 1996.

11. Gmyrek H, Bourauel C Fau - Richter G, Richter G Fau - Harzer W, Harzer W. Torque capacity of metal and plastic brackets with reference to materials, application, technology and biomechanics. J Orofac Orthop. 2002;63(2):113-28.

12. S.C. Chow, H. Wang, J. Shao, Sample Size Calculations in Clinical Research, Second Edition, Taylor & Francis2007.

13. L.M. Brauchli, J. Senn C Fau - Ball, A. Ball J Fau - Wichelhaus, A. Wichelhaus, Force levels of 23 nickel-titanium open-coil springs in compression testing, Am J Orthod Dentofacial Orthop. 2011;139(5):601-5

14. W.R. Proffit, H.W. Fields, D.M. Sarver, Contemporary Orthodontics, Elsevier Health Sciences2014.

Chapter 4 Final Discussion

4.1 General Discussion

Understanding the biomechanics of tooth movement is important for clinical orthodontic treatment. Accurately predicting the desired tooth movements from the application of specific forces and moments may improve the efficiency of orthodontic treatment. Increasing the efficiency of orthodontic treatment may have benefits such as decreasing treatment time for patients, less round tripping of the teeth, and less undesirable side effects from unwanted force systems.

The goal of this study was to simulate a maxillary dentition and analyze the forces and moments generated during space generation mechanics in a crowded dentition with a lingual bracket appliance. Malocclusions presenting with crowded teeth in the anterior segment that need space opening mechanics are a common diagnostic finding. Currently there is minimal research regarding orthodontic treatment mechanics with lingual brackets. This is an important area to study, both because the biomechanics of lingual brackets have differences compared to traditional labial systems[1] [2] [3] [4], and to satisfy the patient desire for esthetic orthodontic treatment options[5] [6].

The OSIM allowed the simultaneous data collection of the three dimensional forces and moments for all teeth in the simulated maxillary arch. This study allowed the comparison of different lingual archwire shapes and different space generation treatment mechanics. The results of this study may be of interest for clinicians when planning orthodontic treatment mechanics.

4.2 Study Limitations

The limitations of this in-vitro study must also be taken into consideration. The study does not simulate certain oral environment conditions such as: saliva, PDL compression, cheek, lip, tongue pressures, masticatory forces, interproximal contacts, and patient specific tooth and root morphology. However, clinically there is great variation between these variables from patient to patient, and therefore we would not expect these variables to significantly influence the results of this study. George et al.[7] investigated PDL compliance with an in-vitro study, and found that incorporating a PDL had minimal effect on the clinical relevance of the in-vitro data when measuring moments greater than 5Nmm. While this investigation considered third-order torque mechanics, it is expected that a similar trend would apply to the study considered here. As a result, while there may be a statistical difference in force magnitudes, we do not expect this to be clinically significant when interpreting findings. The effect of not having interproximal contacts could affect the magnitude of the forces and moments observed in this study. Particularly between the first and second premolars, the presence of interproximal contacts may create more resistance to movement of the first premolar. However, the addition of interproximal contacts would not have allowed the OSIM to be set up with an initial zero position with negligible forces and moments on the teeth prior to insertion of the archwires and mechanics. This initial zero position allowed the reproducible set-up of the OSIM to allow comparison between the experimental groups. Therefore, because all of the treatment groups were assembled in the same way, the results of this study are still relevant for comparing the differences between the groups. However, this limitation of this in-vitro study design should be considered when interpreting the results of this study.

This study analyzed the forces and moments of the maxillary first premolars and lateral incisors at the maximum crowded position at the center of resistance of the tooth. This is the static position that the teeth would initially start at in the simulated crowded dentition. Therefore, the results from the OSIM illustrate the initial forces and moments experienced by the teeth in the crowded position when the archwires and mechanics are inserted before tooth movement begins. The rationale for studying this position was to allow a reproducible comparison of the initial forces and moments on the teeth from the insertion of the archwire and treatment mechanics.

4.3 Future Recommendations

This study analyzed the initial in vitro forces and moments during space generation mechanics using a lingual bracket system at the initial crowded position. The study was conducted in this way to allow a reproducible setting for this in-vitro experimental environment. As the teeth align and move from the crowded position, the forces and moments on the teeth will change. It would be interesting for future studies to analyze the forces and moments at different time points throughout the experiment.

The objective of this study was to analyze initial space generation mechanics using round Nickel Titanium archwires. Future studies could explore the force and moment measurements using different archwire materials (e.g. stainless steel) or different archwire dimensions (e.g. rectangular archwires).

There are many other aspects of orthodontic treatment with lingual brackets that could be studied in the future. This study focused on the treatment mechanics involved in initial space opening procedures for a crowded maxillary dentition. Future studies could simulate other clinically relevant orthodontic situations.

References:

1. George RD, Hirani S. Fully-customized lingual appliances: how lingual orthodontics became a viable treatment option. J Orthod. 2013;40 Suppl 1:S8-13.

2. Lombardo L, Arreghini A Fau - Al Ardha K, Al Ardha K Fau - Scuzzo G, Scuzzo G Fau - Takemoto K, Takemoto K Fau - Siciliani G, Siciliani G. Wire load-deflection characteristics relative to different types of brackets. Int Orthod. 2011;9(1):120-39.

3. Geron S, Romano R Fau - Brosh T, Brosh T. Vertical forces in labial and lingual orthodontics applied on maxillary incisors--a theoretical approach. Angle Orthod. 2004;74(2):195-201.

4. Pol TR, Vandekar M, Patil A, Desai S, Shetty V, Hazarika S. Torque Control During Intrusion on Upper Central Incisor in Labial and Lingual bracket System - A 3D Finite Element Study. J Clin Exp Dent. 2018;10(1):e20-e24

5. McDonald F, Cobourne M. Adult orthodontics: perils and pitfalls. Prog Orthod. 2007;8(2):308-13.

6. Kairalla Sa Fau - Galiano A, Galiano A Fau - Paranhos LR, Paranhos LR. Lingual orthodontics as an aesthetic resource in the preparation of orthodontic/surgical treatment. Int J Orthod Milwaukee. 2014;25(2):31-5.

7. M.G. George, D.L. Romanyk, A. George, Y. Li, G. Heo, P.W. Major, J.P. Carey, Comparison of third-order torque simulation with and without a periodontal ligament simulant, Am J Orthod Dentofacial Orthop. 2015;148(3):431-9

Bibliography:

1. Abdi AHA-Ohoo, Motamedian SR, Balaghi E, Nouri MA-OhooX. The effect of occlusogingival placement of clinical bracket points on the adaptation of a straight wire to the lingual arch form. Korean Journal of Orthodontics. 2018;48(4):236

2. Alobeid A, El-Bialy T, Khawatmi S, Dirk C, Jager A, Bourauel C. Comparison of the force levels among labial and lingual self-ligating and conventional brackets in simulated misaligned teeth. Eur J Orthod. 2017;39(4):419-425.

3. Alobeid A, El-Bialy T, Reimann S, Keilig L, Cornelius D, Jager A et al. Comparison of the efficacy of tooth alignment among lingual and labial brackets: an in vitro study. Eur J Orthod. 2018;40(6):660-665.

4. Alsulaiman AA, Kaye E, Jones J, Cabral H, Leone C, Will L et al. Incisor malalignment and the risk of periodontal disease progression. Am J Orthod Dentofacial Orthop. 2018;153(4):512-522

5. A.M. Schwarz, Tissue changes incidental to orthodontic tooth movement, International Journal of Orthodontia, Oral Surgery and Radiography 18(4) (1932) 331-352.

6. Ata-Ali F, Cobo T, De Carlos F, Cobo J, Ata-Ali J. Are there differences in treatment effects between labial and lingual fixed orthodontic appliances? A systematic review and meta-analysis. BMC Oral Health. 2017;17(1):133

7. Badawi H. The use of multi-axis force transducers for orthodontic force and moment identification. Edmonton, AB, Canada: University of Alberta 2009. [thesis]

8. Badawi HM, Toogood RW, Carey JPR, Heo G, Major PW. Three-dimensional orthodontic force measurements. American Journal of Orthodontics and Dentofacial Orthopedics 2009;136:518-528.

9. Bock NC, Ruf S, Wiechmann D, Jilek T. Dentoskeletal effects during Herbst-Multibracket appliance treatment: a comparison of lingual and labial approaches. Eur J Orthod. 2016;38(5):470-7.

10. Bonnick AM, Nalbandian M Fau - Siewe MS, Siewe MS. Technological advances in nontraditional orthodontics. Dent Clin North Am. 2011;55(3):571-84

11. Bourauel C, Drescher D Fau - Thier M, Thier M. An experimental apparatus for the simulation of three-dimensional movements in orthodontics. J Biomed Eng. 1992;14(5):371-8.

12. Bourke A, Daskalogiannakis J Fau - Tompson B, Tompson B Fau - Watson P, Watson P. Force characteristics of nickel-titanium open-coil springs. Am J Orthod Dentofacial Orthop. 2010;138(2):142.e1-7

13. Brauchli LM, Senn C Fau - Ball J, Ball J Fau - Wichelhaus A, Wichelhaus A. Force levels of 23 nickel-titanium open-coil springs in compression testing. Am J Orthod Dentofacial Orthop. 2011;139(5):601-5.

14. Casa MA, Faltin Rm Fau - Faltin K, Faltin K Fau - Sander FG, Sander Fg Fau - Arana-Chavez VE, Arana-Chavez VE. Root resorptions in upper first premolars after application of continuous torque moment. Intra-individual study. J Orofac Orthop. 2001;62(4):285-95.

15. Chatoo A. A view from behind: a history of lingual orthodontics. J Orthod. 2013;40 Suppl 1:S2-7.

16. Fuck LM, Wiechmann D Fau - Drescher D, Drescher D. Comparison of the initial orthodontic force systems produced by a new lingual bracket system and a straight-wire appliance. J Orofac Orthop. 2005;66(5):363-76

17. Fok J, Toogood Rw Fau - Badawi H, Badawi H Fau - Carey JP, Carey Jp Fau - Major PW, Major PW. Analysis of maxillary arch force/couple systems for a simulated high canine malocclusion: Part 1. Passive ligation. Angle Orthod. 2011;81(6):953-9.

18. Fok J, Toogood Rw Fau - Badawi H, Badawi H Fau - Carey JP, Carey Jp Fau - Major PW, Major PW. Analysis of maxillary arch force/couple systems for a simulated high canine malocclusion: Part 2. Elastic ligation. Angle Orthod. 2011;81(6):960-5.

19. Fujita K. Multilingual-bracket and mushroom arch wire technique. A clinical report. Am J Orthod. 1982;82(2):120-40.

20. Fujita K. New orthodontic treatment with lingual bracket mushroom arch wire appliance. Am J Orthod. 1979;76(6):657-75.

21. Gameiro GH, Magalhaes IB, Szymanski MM, Andrade AS. Is the main goal of mastication achieved after orthodontic treatment? A prospective longitudinal study. Dental Press J Orthod. 2017;22(3): 72–78.

22. George RD, Hirani S. Fully-customized lingual appliances: how lingual orthodontics became a viable treatment option. J Orthod. 2013;40 Suppl 1:S8-13.

23. Geron S, Romano R Fau - Brosh T, Brosh T. Vertical forces in labial and lingual orthodontics applied on maxillary incisors--a theoretical approach. Angle Orthod. 2004 Apr;74(2):195-201.

24. Gmyrek H, Bourauel C Fau - Richter G, Richter G Fau - Harzer W, Harzer W. Torque capacity of metal and plastic brackets with reference to materials, application, technology and biomechanics. J Orofac Orthop. 2002;63(2):113-28.

25. Gorman JC, Smith RJ. Comparison of treatment effects with labial and lingual fixed appliances. Am J Orthod Dentofacial Orthop. 1991;99(3):202-9.

26. Kairalla Sa Fau - Galiano A, Galiano A Fau - Paranhos LR, Paranhos LR. Lingual orthodontics as an aesthetic resource in the preparation of orthodontic/surgical treatment. Int J Orthod Milwaukee. 2014;25(2):31-5.

27. Kitaura H, Kimura K, Ishida M, Sugisawa H, Kohara H, Yoshimatsu M et al. Effect of Cytokines on Osteoclast Formation and Bone Resorption during Mechanical Force Loading of the Periodontal Membrane. Scientific World Journal. 2014;2014:617032.

28. Kuo B, Takakuda K Fau - Miyairi H, Miyairi H. Development of an orthodontic simulator for measurement of orthodontic forces. J Med Dent Sci. 2001;48(1):15-21.

29. Kyteas PG, McKenzie WS, Waite PD, Kau CH. Comprehensive treatment approach for condylar hyperplasia and mandibular crowding with custom lingual braces and 2-jaw surgery. Am J Orthod Dentofacial Orthop. 2017;151(1):174-185.

30. Lee D Fau - Heo G, Heo G Fau - El-Bialy T, El-Bialy T Fau - Carey JP, Carey Jp Fau - Major PW, Major Pw Fau - Romanyk DL, Romanyk DL. Initial forces experienced by the anterior and posterior teeth during dental-anchored or skeletal-anchored en masse retraction in vitro. Angle Orthod. 2017;87(4):549-555.

31. Liang W, Rong Q, Lin J, Xu B. Torque control of the maxillary incisors in lingual and labial orthodontics: A 3-dimensional finite element analysis. American Journal of Orthodontics and Dentofacial Orthopedics 2009;135:316-322.

32. L.M. Brauchli, J. Senn C Fau - Ball, A. Ball J Fau - Wichelhaus, A. Wichelhaus, Force levels of 23 nickel-titanium open-coil springs in compression testing, Am J Orthod Dentofacial Orthop. 2011;139(5):601-5

33. Lombardo L, Arreghini A Fau - Al Ardha K, Al Ardha K Fau - Scuzzo G, Scuzzo G Fau - Takemoto K, Takemoto K Fau - Siciliani G, Siciliani G. Wire load-deflection characteristics relative to different types of brackets. Int Orthod. 2011;9(1):120-39

34. Lombardo L, Carlucci A, Palone MA-Ohoo, Mollica F, Siciliani G. Stiffness comparison of mushroom and straight SS and TMA lingual archwires. Prog Orthod. 2016;17(1):27.

35. Lombardo L, Marafioti M Fau - Stefanoni F, Stefanoni F Fau - Mollica F, Mollica F Fau - Siciliani G, Siciliani G. Load deflection characteristics and force level of nickel titanium initial archwires. Angle Orthod. 2012;82(3):507-21

36. Lombardo L, Scuzzo G Fau - Arreghini A, Arreghini A Fau - Gorgun O, Gorgun O Fau - Ortan YO, Ortan Yo Fau - Siciliani G, Siciliani G. 3D FEM comparison of lingual and labial orthodontics in en masse retraction. Prog Orthod. 2014;15(1):38

37. Lombardo L, Wierusz W Fau - Toscano D, Toscano D Fau - Lapenta R, Lapenta R Fau - Kaplan A, Kaplan A Fau - Siciliani G, Siciliani G. Frictional resistance exerted by different lingual and labial brackets: an in vitro study. Prog Orthod. 2013;14:37

38. Lossdorfer S, Bieber C Fau - Schwestka-Polly R, Schwestka-Polly R Fau - Wiechmann D, Wiechmann D. Analysis of the torque capacity of a completely customized lingual appliance of the next generation. Head Face Med. 2014;10:4.

39. Major PW, Toogood RW, Badawi HM, Carey JP, Seru S. Effect of wire size on maxillary arch force/couple systems for a simulated high canine malocclusion. J Orthod. 2014;41(4):285-91

40. Manhartsberger C, Seidenbusch W. Force delivery of Ni-Ti coil springs. Am J Orthod Dentofacial Orthop. 1996;109(1):8-21.

41. McDonald F, Cobourne M. Adult orthodontics: perils and pitfalls. Prog Orthod. 2007;8(2):308-13.

42. Meeran NA. Biological response at the cellular level within the periodontal ligament on application of orthodontic force - An update. Journal of orthodontic science 2012;1:2-10.

43. M.G. George, D.L. Romanyk, A. George, Y. Li, G. Heo, P.W. Major, J.P. Carey, Comparison of third-order torque simulation with and without a periodontal ligament simulant, Am J Orthod Dentofacial Orthop. 2015;148(3):431-9

44. Mencattelli M, Donati E, Spinelli P, Cultrone M, Luzi C, Cantarella D et al. Measuring 3D-orthodontic actions to guide clinical treatments involving coil springs and miniscrews. Biomed Microdevices. 2017;19(1):14.

45. Menghi C, Planert J Fau - Melsen B, Melsen B. 3-D experimental identification of force systems from orthodontic loops activated for first order corrections. Angle Orthod. 1999;69(1):49-57.

46. Mistakidis I, Katib H, Vasilakos G, Kloukos D, Gkantidis N. Clinical outcomes of lingual orthodontic treatment: a systematic review. European Journal of Orthodontics 2016;38:447-458.

47. Nanda R. Biomechanics in Clinical Orthodontics Philadelphia: WB Saunders Co; 1996.

48. Nassif CE, Cotrim-Ferreira A, Conti ACCF, Valarelli DP, Cardoso MdA, Almeida-Pedrin RRd. Comparative study of root resorption of maxillary incisors in patients treated with lingual and buccal orthodontics. The Angle Orthodontist 2017;87:795-800.

49. Ogura M, Kamimura H Fau - Al-Kalaly A, Al-Kalaly A Fau - Nagayama K, Nagayama K Fau - Taira K, Taira K Fau - Nagata J, Nagata J Fau - Miyawaki S et al. Pain intensity during the first 7 days following the application of light and heavy continuous forces. Eur J Orthod. 2009;31(3):314-9

50. Owen B, Gullion G, Heo G, Carey JP, Major PW, Romanyk DL. Measurement of forces and moments around the maxillary arch for treatment of a simulated lingual incisor and high canine malocclusion using straight and mushroom archwires in fixed lingual appliances. Eur J Orthod. 2017;39(6):665-672.

51. Papageorgiou SNA-Ohoo, Golz L, Jager A, Eliades T, Bourauel C. Lingual vs. labial fixed orthodontic appliances: systematic review and meta-analysis of treatment effects. Eur J Oral Sci. 2016;124(2):105-18.

52. Park JH, Lee Yk Fau - Lim B-S, Lim Bs Fau - Kim C-W, Kim CW. Frictional forces between lingual brackets and archwires measured by a friction tester. Angle Orthod. 2004;74(6):816-24.

53. Pol TR, Vandekar M, Patil A, Desai S, Shetty V, Hazarika S. Torque Control During Intrusion on Upper Central Incisor in Labial and Lingual bracket System - A 3D Finite Element Study. J Clin Exp Dent. 2018;10(1):e20-e24.

54. Ren Y, Maltha Jc Fau - Kuijpers-Jagtman AM, Kuijpers-Jagtman AM. Optimum force magnitude for orthodontic tooth movement: a systematic literature review. Angle Orthod. 2003;73(1):86-92.

55. Rosvall MD, Fields Hw Fau - Ziuchkovski J, Ziuchkovski J Fau - Rosenstiel SF, Rosenstiel Sf Fau - Johnston WM, Johnston WM. Attractiveness, acceptability, and value of orthodontic appliances. Am J Orthod Dentofacial Orthop. 2009;135(3):276.e1-12

56. Rygh P Fau - Bowling K, Bowling K Fau - Hovlandsdal L, Hovlandsdal L Fau - Williams S, Williams S. Activation of the vascular system: a main mediator of periodontal fiber remodeling in orthodontic tooth movement. Am J Orthod. 1986;89(6):453-68.

57. S.C. Chow, H. Wang, J. Shao, Sample Size Calculations in Clinical Research, Second Edition, Taylor & Francis2007.

58. Schneevoigt R, Haase A Fau - Eckardt VL, Eckardt Vl Fau - Harzer W, Harzer W Fau - Bourauel C, Bourauel C. Laboratory analysis of superelastic NiTi compression springs. Med Eng Phys. 1999;21(2):119-25.

59. Seru S, Romanyk DL, Toogood RW, Carey JP, Major PW. Effect of ligation method on maxillary arch force/moment systems for a simulated lingual incisor malalignment. Open Biomed Eng J. 2014;8:106-13

60. Shpack N, Geron S, Floris I, Davidovitch M, Brosh T, Vardimon AD. Bracket Placement in Lingual vs Labial Systems and Direct vs Indirect Bonding. The Angle Orthodontist 2007;77:509-517.

61. Sifakakis I, Pandis N Fau - Makou M, Makou M Fau - Katsaros C, Katsaros C Fau - Eliades T, Eliades T Fau - Bourauel C, Bourauel C. A comparative assessment of forces and moments generated by lingual and conventional brackets. Eur J Orthod. 2013;35(1):82-6

62. Smith Rj Fau - Burstone CJ, Burstone CJ. Mechanics of tooth movement.

63. Steinbach G, Armstrong D Fau - Kharbanda OP, Kharbanda Op Fau - Petocz P, Petocz P Fau - Darendeliler MA, Darendeliler MA. An investigation of the forces used by clinicians to open spaces with coil springs. Aust Orthod J. 2006;22(2):115-20.

64. Sung SJ, Baik HS, Moon YS, Yu HS, Cho YS. A comparative evaluation of different compensating curves in the lingual and labial techniques using 3D FEM. American Journal of Orthodontics and Dentofacial Orthopedics 2003;123:441-450.

65. Taibah SM, Al-Hummayani FM. Effect of malocclusion on the self-esteem of adolescents. J Orthod Sci. 2017;6(4): 123–128.

66. Talic NF. Adverse effects of orthodontic treatment: A clinical perspective. The Saudi dental journal 2011;23:55-59.

67. von Fraunhofer JA, Bonds Pw Fau - Johnson BE, Johnson BE. Force generation by orthodontic coil springs. Angle Orthod. 1993;63(2):145-8

68. Weltman B, Vig Kw Fau - Fields HW, Fields Hw Fau - Shanker S, Shanker S Fau - Kaizar EE, Kaizar EE. Root resorption associated with orthodontic tooth movement: a systematic review. Am J Orthod Dentofacial Orthop. 2010;137(4):462-76

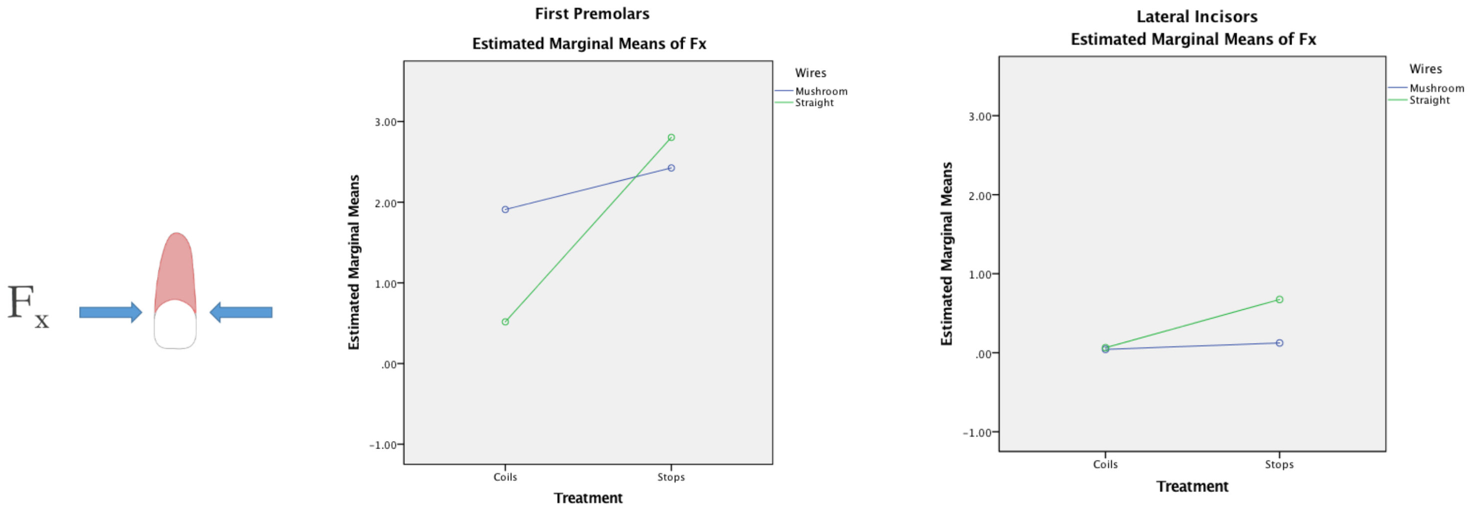
69. Wilmes B, Nienkemper M Fau - Mazaud-Schmelter M, Mazaud-Schmelter M Fau - Renger S, Renger S Fau - Drescher D, Drescher D. Combined use of Beneslider and lingual braces, mechanical aspects and procedures. Orthod Fr. 2013;84(4):347-59.

70. W.R. Proffit, H.W. Fields, D.M. Sarver, Contemporary Orthodontics, Elsevier Health Sciences2014.

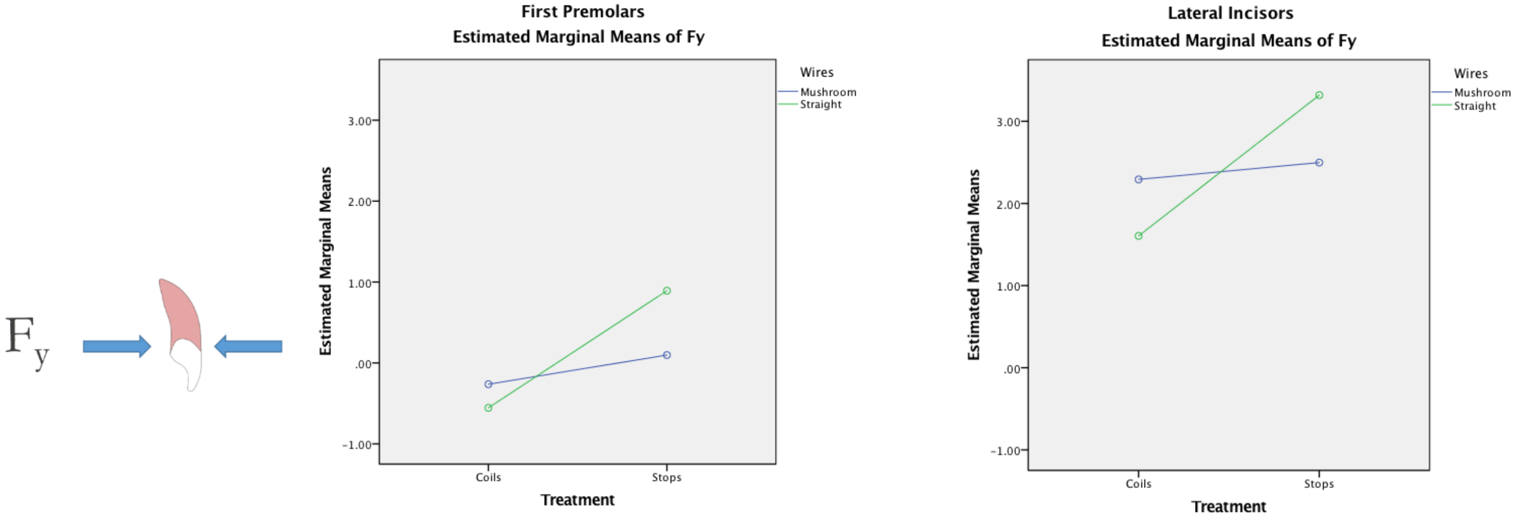
Appendix

1.1 Interaction between Wire Type and Treatment Type

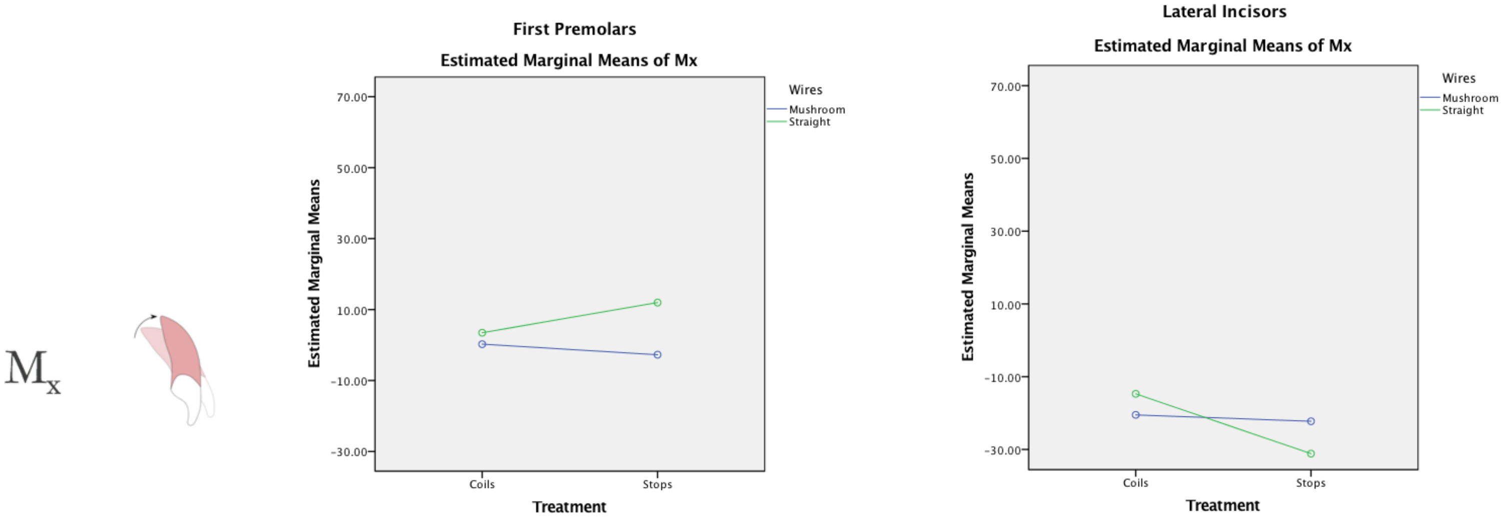
The relationship between treatment type and wire type with regards to the mean F_x, F_y, M_x, M_y, and M_z for maxillary first premolars and maxillary lateral incisors is assessed at the maximum crowded position. To visualize this, Fig. 1.1 (i-v) displays the profile plots for mean F_x, F_y, M_x, M_y, and M_z of maxillary first premolars and maxillary lateral incisors for the different treatments and archwires. Many of the profile plots have lines that intersect, which suggests that there is convincing evidence against our null hypothesis H_{o1}, and that there is a significant interaction between treatments and archwires for the first premolars and lateral incisors. This is confirmed by values presented in Table 3.1 and 3.2, in which many show statistical significance with p-values<0.05.



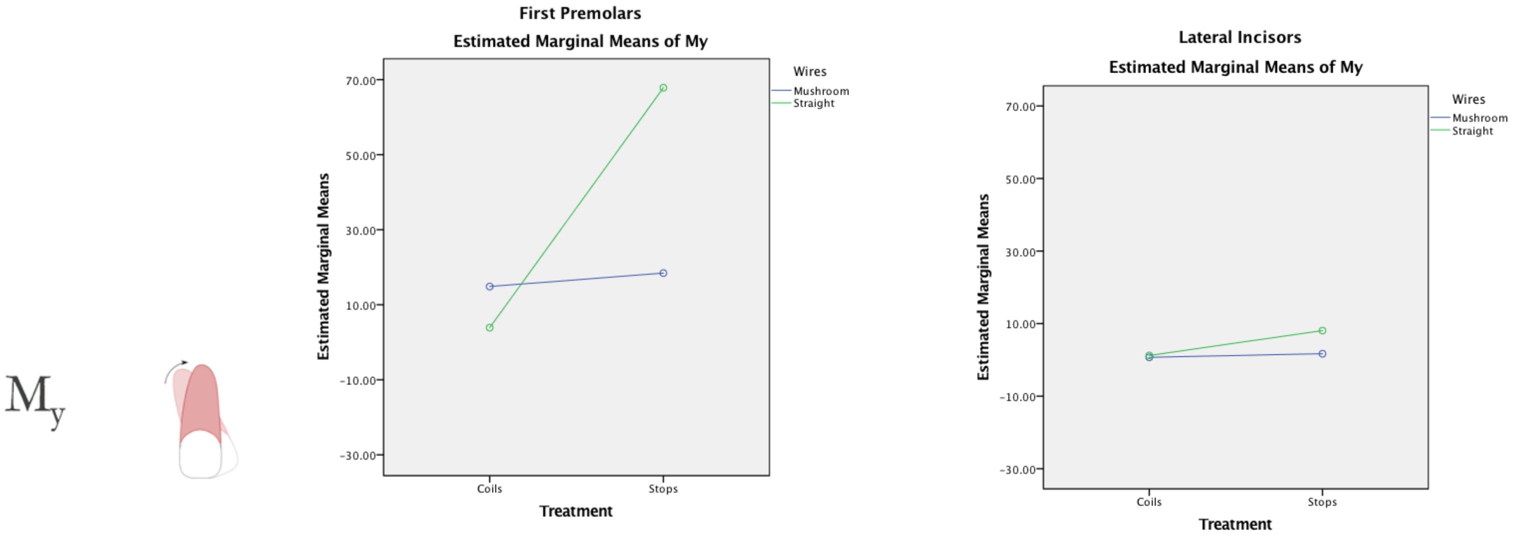
i)


F_y
First Premolars
Estimated Marginal Means of Fy
Estimated Marginal Means
3.00
2.00
1.00
.00
-1.00
Coils
Stops
Treatment
Wires
Mushroom
Straight
Lateral Incisors
Estimated Marginal Means of Fy
Estimated Marginal Means
3.00
2.00
1.00
.00
-1.00
Coils
Stops
Treatment
Wires
Mushroom
Straight

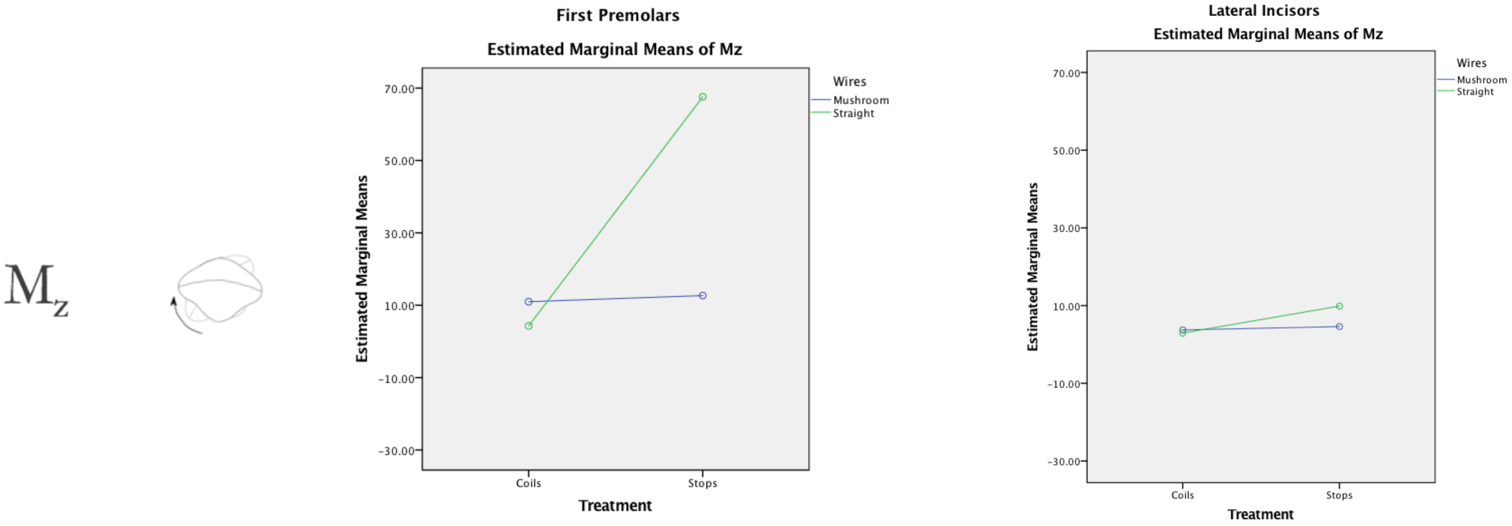
ii)


M_x
First Premolars
Estimated Marginal Means of Mx
Estimated Marginal Means
70.00
50.00
30.00
10.00
-10.00
-30.00
Coils
Stops
Treatment
Wires
Mushroom
Straight
Lateral Incisors
Estimated Marginal Means of Mx
Estimated Marginal Means
70.00
50.00
30.00
10.00
-10.00
-30.00
Coils
Stops
Treatment
Wires
Mushroom
Straight

iii)



iv)



v)

Figure 1.1 (i-v) Profile Plots of estimated marginal means for Fx, Fy, Mx, My, Mz at the maximum crowded position for treatment types and wire types of maxillary first premolars and lateral incisors

2.1 Straight Archwire Stops Data

The arrows in Fig. 2.1 show the two distinct patterns of F_x values that occurred for the first premolars (tooth 1-4 and 2-4). In Fig. 2.1 a), for tooth 1-4 and 2-4, there are consistently increasing values until the maximum crowded position, and then the values consistently decrease as the experiment moved back to the initial passive position. In Fig. 2.1 b), tooth 1-4 and 2-4 appear to reach a threshold where the F_x values that decrease abruptly, and then increased again. It appears that at a certain threshold, the wire would move out of its original plane, the wire would buckle, and then move back into the original plane again.

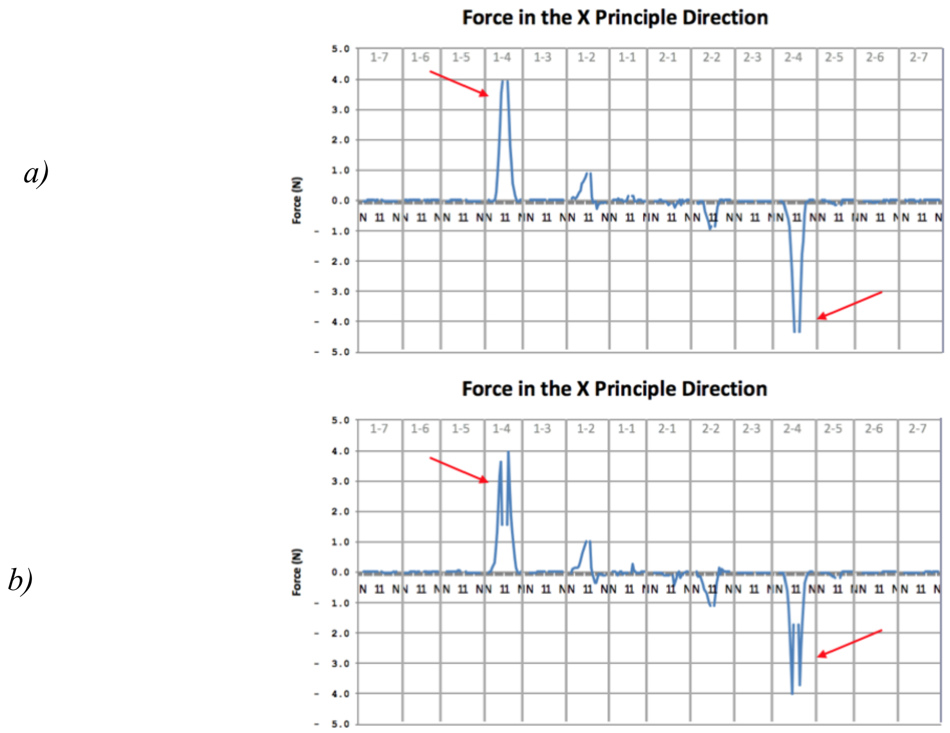


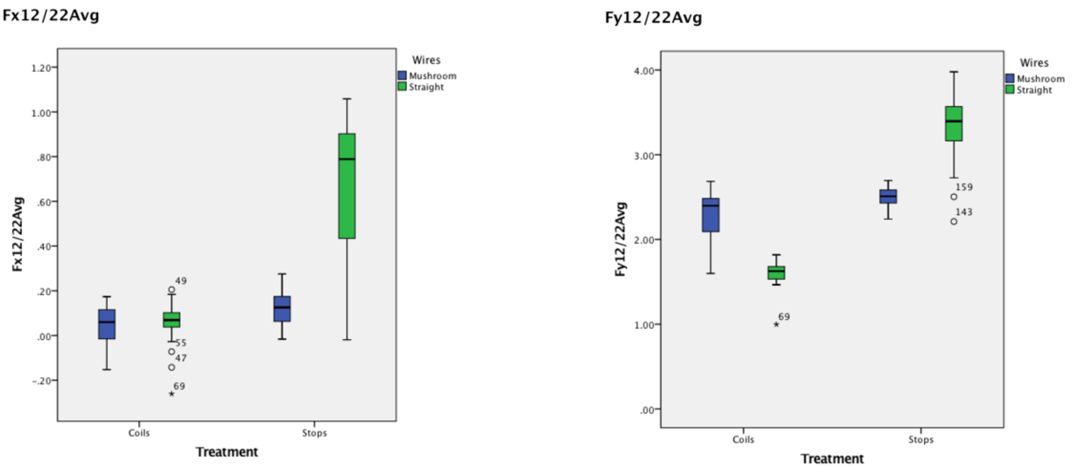
Figure 2.1 Straight archwire stops result

a) This trial did not reach the threshold and the wire did not buckle out of plane; the force data for tooth 1-4 and 2-4 (first premolars) increases and decreases steadily b) This trial reached a threshold in which the wire buckled out of the original plane; this is seen by a distinct drop in F_x, and then increase in F_x for tooth 1-4 and 2-4

3.1 Additional Statistical Analyses Figures and Tables

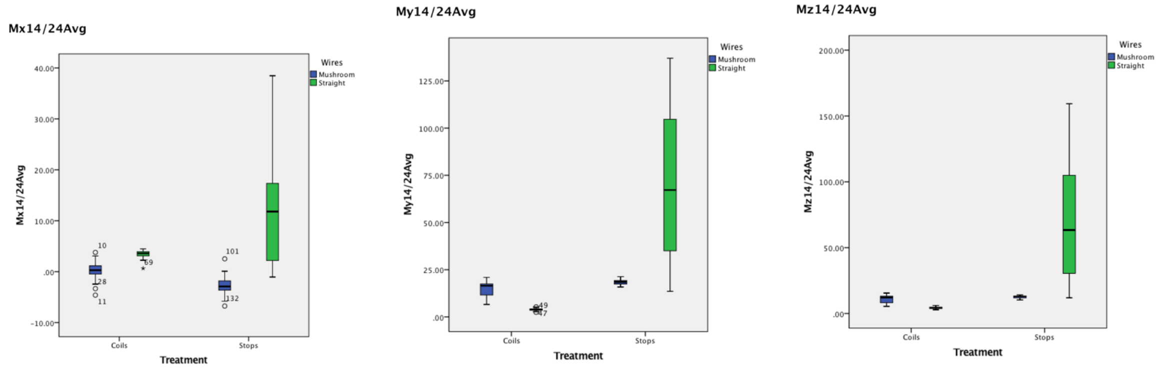
Table 3.1 Results from MANOVA Overall Test

Factors	**Pillai's Trace p-value**
First Premolars: Treatment	<0.001
First Premolars: Wires	<0.001
First Premolars: Treatment*Wires	<0.001
Lateral Incisors: Treatment	<0.001
Lateral Incisors: Wires	<0.001
Lateral Incisors: Treatment*Wires	<0.001



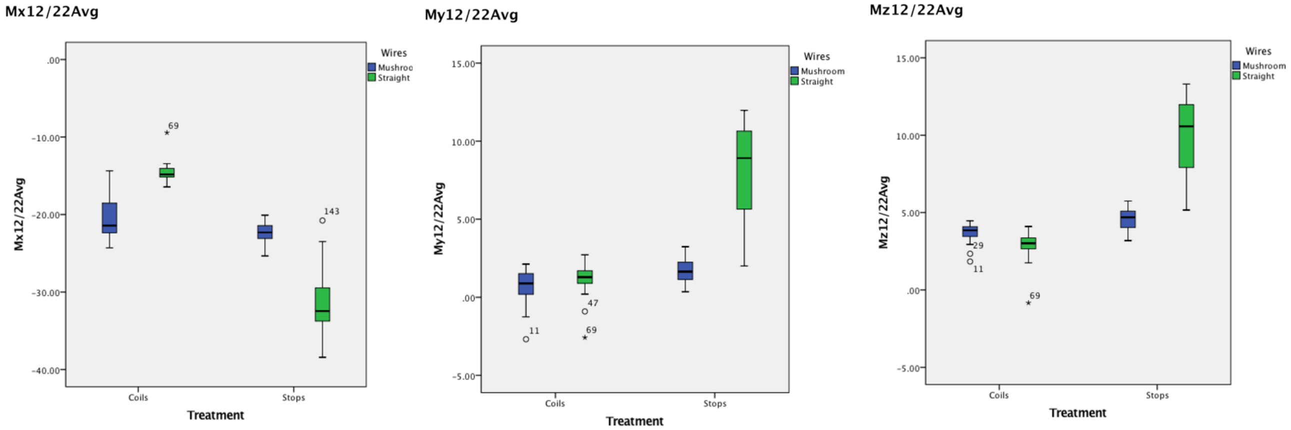
a) *b)*

Figure 3.1 a) Boxplot of mean F_x values of lateral incisors for the different treatment types and archwire types b) Boxplot of mean F_y values of lateral incisors for the different treatment types and archwire types



a) b) c)

Figure 3.2 a) Boxplot of mean M_x values of first premolars for the different treatment and archwire types b) Boxplot of mean M_y values of first premolars for the different treatment and archwire types c) Boxplot of mean M_z values of first premolars for the different treatment and archwire types



a) b) c)

Figure 3.3 a) Boxplot of mean M_x values of lateral incisors for the different treatment and archwire types b) Boxplot of mean M_y values of lateral incisors for the different treatment and archwire types c) Boxplot of mean M_z values of lateral incisors for the different treatment and archwire types