Simulation of Initial Forces and Moments on a Curve of Spee Malocclusion with Labial and Lingual Orthodontic Appliances

by

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ABSTRACT

OBJECTIVES: Orthodontic movement is determined by the acting forces and moments exerted onto teeth, which are difficult to predict and calculate with continuous archwires. Levelling the curve of Spee is a fundamental objective in orthodontic treatment. The forces and moments exerted by labial and lingual orthodontic fixed appliances using three archwire forms (labial straightwire, lingual straightwire, and lingual mushroom) on mandibular teeth in a curve of Spee malposition were compared. An increased understanding may have clinical implications pertaining to orthodontic appliance design in preventing adverse effects such as undesirable tooth movement and root resorption.

METHODS: The Orthodontic SIMulator (OSIM) measured the three-dimensional forces and moments on each tooth of a mandibular arch (excluding third molars) set in a curve of Spee malposition with the first premolar intruded 1.5mm and the canine and second premolar intruded 0.75mm. Labial and lingual brackets were bonded to the mechanical teeth initially in a levelled position. Attached load cells measured the forces and moments as the dental analogs, with an archwire engaged, moved to the curve of Spee position. Three treatment groups (archwire forms) were assessed: labial straightwire, lingual straightwire, and lingual mushroom. The primary forces and moments of interest were occlusal-gingival forces (F_z), labial-lingual forces (F_y), and labial-lingual moments (M_x).

RESULTS: Similarities and differences were observed between the archwire forms. All archwire forms generally exerted forces in the same direction on the mandibular teeth but at different magnitudes. Teeth positioned below the occlusal plane received occlusal forces relative to their displacement, while the lateral incisor received large gingival forces with all groups. The lowest force magnitudes were noted with labial straightwires at each tooth position. The first premolar and first molar had different directional labial-lingual moments between labial and the two lingual archwire forms. The standard deviations of horizontal moments on the first premolar were substantially large with lingual archwire forms.

CONCLUSION: The initial forces and moments of interest (F_z, F_y, and M_x) on mandibular mechanical teeth in a curve of Spee malposition were different between labial and lingual archwire forms. The majority of the recorded forces and moments were above the clinically significant threshold for tooth movement. Similar pattern of labial-lingual and occlusal-gingival forces were exerted been labial and lingual archwire forms. The lateral incisor received large gingival forces and labial crown tipping forces, which has increased concerns of root resorption. Labial straightwires exerted the lowest magnitudes at each tooth position and have increased transverse effects on the crowns of posterior teeth. With both lingual archwire forms, the first premolar resulting labial-lingual incliniation could be highly variable, as it had large standard deviation of labial-lingual moments.

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LIST OF SYMBOLS AND ABBREVIATIONS USED

FEM – finite element method

NiTi – nickel titanium

C_{res} – center of resistance

C_{rot} – center of rotation

F_x, F_y, F_z – force along the x-, y-, z- axis

M_x, M_y, M_z – moment around the x-, y-, z- axis

OSIM – Orthodontic SIMulator

OMSS – Orthodontic Measurement and Simulation System

MANOVA – multivariate analysis of variance

CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

Orthodontic malocclusions of different etiologies (ie. dental, skeletal or functional) are corrected with the goal of aligning teeth in a functional, healthy, and esthetic position. Labial brackets are the most used appliance[1]. The direct line of sight with labial appliances provides clinicians with easy insertion and handling that decrease appointment chairtimes[2]. However, being on the labial surface, the cheek-side of teeth, is unsightly.

With an increase in global demand for treatment, orthodontists and patients are continually seeking treatments that are more esthetic and efficient[3]. Lingual orthodontics was introduced in the 1980's for patients seeking a more concealed appearance[4]. Placing brackets on the lingual surfaces of teeth allows for inconspicuous treatment and reduces risk of white spot lesions and decalcification[5]. The learning curve for clinical use and maintenance is steep due to the variability in anatomical morphology of teeth's lingual surfaces, which leads to issues with bracket adaptation and handling[3]. Bonding lingual brackets is more difficult because of having to control the tongue, maintaining a dry environment, and the lack of direct line of sight. Recent technological advances in resin bonding and customization of brackets and archwires have mitigated many of these concerns[3]. Development of customized brackets and wires that are less bulky have improved bond strength and clinical handling[6,7].

Orthodontic biomechanics of forces and moments is fundamental to tooth movement[8]. Its understanding is critical for the prediction of treatment outcomes and reducing unwanted side effects[8]. Inappropriate application can increase treatment duration, alveolar bone loss, root resorption, and patient discomfort[9,10]. A force is defined as a load applied to an object that will tend to move its spatial position[7]. Tooth movement depends on the location of the tooth's center of resistance (C_{res}), conceptually defined in orthodontics as the point through which the collective mechanical effect of supporting structures is assumed to act. In this way, a force passing directly through the C_{res} would generate a pure translational, or bodily, tooth movement[8]. A force acting at a distance from C_{res} generates a moment, the measure of the tendency to rotate around that point or axis[8]. The nature of the applied force and/or moment relative to a tooth's C_{res} creates different tooth movements, such as translation, tipping, and root torque[8]. In addition, the magnitudes of these forces and moments are ideally above a minimum threshold that produces the most efficient tooth movement and not extreme enough to cause tissue damage or pain[6,11,12].

Lingual and labial appliances have fundamentally different biomechanics because of tooth anatomy, bracket location (Figure 1.1), and archwire forms (Figure 1.2)[13]. Lingual surfaces of teeth are concave with high individual morphological variations[6], such as tooth thickness and

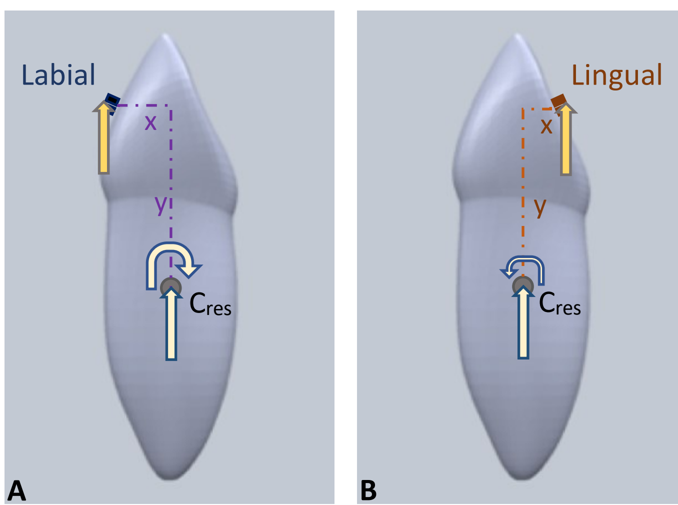

Figure 1.1 Occlusal force (yellow arrows) at the bracket and its equivalent forces and moments (white arrows) at the C_{res}. **A,** Labial bracket. **B,** Lingual bracket. Note the size and direction of the moments (curved arrow) differences with the same orthodontic force because of the bracket position.

marginal ridge prominences. In contrast, labial surfaces are convex with less diversity, allowing for more accurate standardized bracket design using mean values[6].

The bracket location affects the resultant vector in direction and magnitude from the same orthodontic load (Figure 1.1). For example, the same intrusive force on the labial and lingual surface would theoretically create labial and lingual crown tipping respectively[13]. Because lingual brackets are closer than labial brackets to the center of resistance of a maxillary incisor, the moments would also be smaller in magnitude[13].

The shape and size of labial and lingual archwires are also different to adapt to their bracket positions (Figure 1.2). Labial surfaces of teeth follow a parabola; lingual surfaces have an irregular pattern due to distinct tooth thicknesses seen as steps, primarily between the canines and first premolars. Straight (parabolic) archwires are used for both systems, which the lingual version compensates with a thicker canine composite bond. Otherwise, a mushroom archwire is used where the archwire is straight from canine to canine and first premolar to second molars with a labial-lingual step bend in between. Compared to labial archwires, both lingual archwire forms have narrower widths and smaller inter-bracket distances that increase

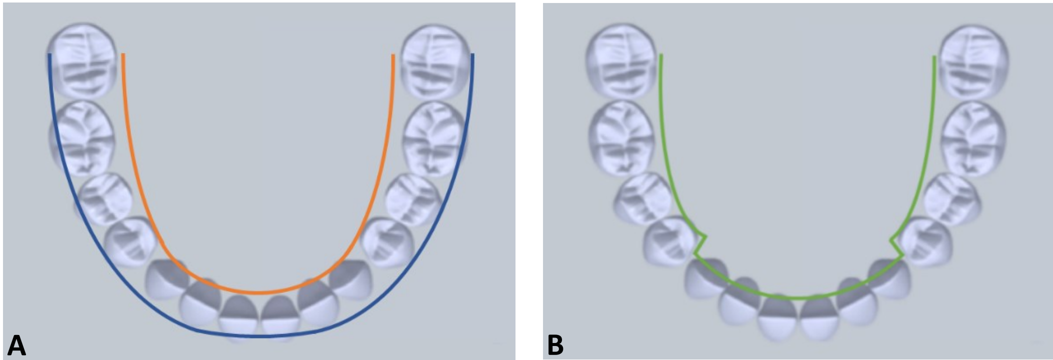

Figure 1.2 Archwire forms **A.** Labial (blue) and lingual (orange) straightwires **B.** Lingual mushroom wire

archwire stiffness due to a shorter span between teeth, creating larger forces and moments[7,14,15].

Lingual appliance treatment outcomes have been compared to the more established labial appliances. Research has shown lingual appliance treatment to be a viable alternative with successful results[3] and no differences with respect to risk of root resorption and temporomandibular disorders[16]. Clinical accuracy and duration are similar[17,18], with minor differences on incisal inclination[18,19], inter-canine and inter-molar widths[2].

A flat curve of Spee is considered one of six key treatment goals of comprehensive orthodontic treatment[20]. The curve of Spee is the arc of a curved plane tangent to the buccal cusps and incisal edges of the mandibular teeth in the sagittal plane (Figure 1.3)[21]. The severity of this curve is measured as the largest distance from the cusp tip of the farthest tooth to the reference line of the occlusal plane. Among the many benefits are proper biomechanical function, muscular balance, balanced occlusal forces, proper intercuspation, and normal functional movement of the mandible[22]. From an orthodontic treatment perspective, the curve of Spee has arch length[23,24], incisor inclination[23], inter-canine width[25], and deepbite[21] considerations.

A levelled curve of Spee is considered relatively stable regardless of initial severity[26]. It is clinically achieved by a combination of mandibular molar intrusion, premolar extrusion, and incisor proclination and intrusion[22,27,28] (Figure 1.3). There has been limited research comparing lingual and labial appliances to level the curve of Spee.

It is understandably difficult to complete a high-quality clinical trial comparing labial and lingual appliances with low risk of bias due to inherent study design limitations. It is almost impossible to expect patient/clinician blinding to the appliance used. Smaller sample sizes are common due to the increased length and cost of orthodontic treatment, which makes managing confounding factors a challenge. It has been proposed that it may be more beneficial to obtain a consensus to match an orthodontic approach to specific characteristics of a malocclusion[18] and further examine the differences in mechanics[3]. The analysis of contemporary treatment with continuous archwires is also complicated, as it is too complex to precisely calculate and predict the numerous forces and moments involved in equilibrium[7].

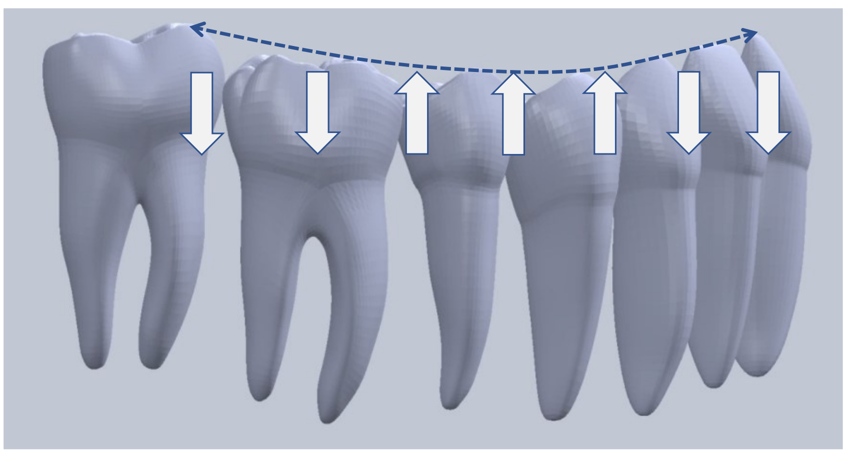

Figure 1.3 The curve of Spee, indicated by the dashed line following the mandibular buccal cusps and incisal edges, and the arrows illustrate the general dental extrusion and intrusion during levelling.

Because of the difficulty in predicting forces and moments generated during treatment, experimental simulations of orthodontic movement are beneficial to provide quantitative data to supplement clinical research. Analyzing the stress and strain of the periodontium under orthodontic loads has been useful with techniques such as finite element method and photo-elasticity[29–31]. The finite element method uses extensive numerical computations to predict resultant tooth movement, but the interpretations are heavily dependent on material properties, physical geometry, and mechanics assumptions[32]. With photo-elasticity, the periodontal stress and strain is quantified by fringe patterns of teeth embedded within a photosensitive medium. It has an added advantage of realistic incorporation of clinical bracket-archwire interactions[33] but is less applicable for complete three-dimensional simulations with increased complexity[30,34].

Mechanical apparatuses have been developed to directly measure three-dimensional orthodontic force systems, but many measure only a few teeth per simulation[35–38]. The Orthodontic Simulator (OSIM) is an in vitro experimental apparatus that simultaneously measures the three-dimensional forces and moments expressed onto individual teeth of a whole dental arch by orthodontic appliances with precision and accuracy[39]. Developed at the University of Alberta, it has compared the orthodontic biomechanical effects of factors such as ligation methods[40], archwire sizes, and anchorage[41]. This study simulated a curve of Spee occlusion with both lingual and labial appliances using the OSIM to increase the understanding of the acting forces and moments during orthodontic levelling.

1.2 RESEARCH OBJECTIVES

This research study aims to determine the differences in forces and moments of interest between archwire forms of labial and lingual orthodontic appliances to level the curve of Spee. The results could help understand the potential tooth movement between lingual and labial orthodontics. Clinicians can therefore make more informed decisions on appliance design and treatment modalities to improve treatment effectiveness and reduce undesirable side effects.

1.3 STUDY DESIGN

This study was designed to determine the forces and moments generated by different archwire forms used by labial and lingual appliances to level a curve of Spee, measured in vitro with the OSIM. The study compared three archwire forms using the same archwire material and dimensions:

1. Labial straightwire
2. Lingual straightwire
3. Lingual mushroom

1.4 RESEARCH QUESTIONS

The research purpose of this study is to compare the forces and moments of interest experienced by the mandibular teeth between the three archwire forms. Vertical forces in the occlusal-gingival direction (F_z) and both horizontal forces and moments in the labial-lingual direction (F_y and M_x, respectively) were chosen to be analyzed. Research has shown curve of Spee levelling to be a combination of molar intrusion, premolar extrusion, and incisor intrusion and proclination, as mentioned previously. Labial and lingual loads inducing vertical movement also impact labial-lingual vectors[13]. Forces and moments in the mesial-distal direction were not a primary objective of this study and thus excluded in the analysis.

Primary research questions

1. Are there differences in forces and moments between the archwire forms?

The bracket locations correspond to each respective archwire form and would be different between them. The distance between the load at the bracket-archwire interface and C_{res} is then affected, implicating differences in F_z, F_y, and M_x between the archwire forms.

H_{o1}: there are no differences in F_z, F_y, or M_x levels between the three archwire forms.
H_{a1}: there is a difference in F_z, F_y, or M_x levels between the three archwire forms.

2. Are there differences in forces and moments between tooth position?

With the expected differences in intrusion, extrusion and proclination between mandibular teeth with a curve of Spee, there should be differences in F_z, F_y, and M_x.

H_{o2}: there are no differences in F_z, F_y, or M_x levels between each tooth position.
H_{a2}: there is a difference in F_z, F_y, or M_x levels between each tooth position.

Secondary research question:

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

It would be beneficial to understand the magnitude of any differences that were found in the primary research questions. Quantification aids in understanding the extent of the impact teeth position or archwire form would have on F_z, F_y, or M_x.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Orthodontic fixed appliances can be categorized by its bracket location on a tooth, where labial appliances, or brackets, are placed on the cheek-side of teeth, while lingual appliances are placed on the tongue- or palate-side. Labial appliances are the most common appliance in orthodontics due to the clinician ease of use as the brackets are more accessible and lower in cost[6]. Lingual braces addresses the need for an inconspicuous alternative[42], especially with the rise in esthetic orthodontic treatment demand[3,43,44].

Both appliances are established as viable treatment options for simple and complex cases[45,46] with similar treatment outcome satisfaction and effectiveness[47–49] and no significant differences in complications or adverse risks[48]. However, clinical studies were generally assessed as low quality or high risk of bias due to issues such as lack of blinding, small sample sizes, and study design, which prevents strong conclusions to be made[2,17].

It is still important to understand the biomechanical considerations stemming from the design differences between labial and lingual appliances[6,50]. The forces and moments would differ on the teeth and consequently potentiate different tooth movements seen clinically[51]. Lack of understanding or inappropriate force application could increase treatment duration[8]. As a result, the patient's satisfaction, quality of life, and self-esteem decreases with increases in adverse effects such as caries, root resorption, and gingival inflammation[52–55].

Orthodontic treatment utilizes labial and lingual appliances to correct various misalignments (malocclusions). Dental movement depends on the relationship between three processes: biological, biomechanical, and clinical[56–58]. It is a cumulative response of the dental structures to different force loads that are employed clinically. Research is currently limited in high quality clinical trials analyzing outcomes between lingual and labial appliances[2,17,18] and is in need of further biomechanical comparisons[3].

2.2 BIOLOGY OF TOOTH MOVEMENT

The periodontal ligament (PDL) is a collagenous and fluid-filled supporting structure attached to root cementum, and it supports the tooth within the surrounding alveolar bone[59]. Teeth can experience heavy intermittent forces of short duration, which the PDL transmits over the larger surface area of alveolar bone to prevent displacement under normal masticatory function[7]. However, application of sustained forces can exceed the PDL's adaptive threshold. Tooth movement occurs when sufficient external pressure creates stress and strain within the PDL and stimulates the surrounding bone to remodel[60,61].

Understanding the magnitude and direction of orthodontic forces is fundamental to achieving clinical outcomes in a timely manner and maintain the health of dental soft and hard tissue[8]. Prolonged forces, even of low magnitude, are recognized by osteocytes[62] and initiate a cascade of cellular events within the periodontium[63–65]. Blood flow increases on the tension side as the PDL is stretched, and osteoblasts activate to form bone. On the opposite side, compression decreases the blood flow in the PDL and stimulates the formation of osteoclasts to resorb alveolar bone through the osteocyte mediated mechanism. Lower force magnitudes induce faster tooth movement via frontal resorption[66,67], where the osteoclastic activity initiates within the compressed PDL to resorb surface bone and creates space for a tooth to move into[7].

Excessive forces can overload the periodontium and crush the blood supply[60,63]. With the PDL now hyalinized and necrotic, undermining resorption occurs[68]. The osteoclasts are recruited from adjacent bone instead, and orthodontic movement consequently lags. These heavy forces further activate odontoclastic activity that may cause root resorption and possibly tooth loss[64,69], patient pain[69], and instability of orthodontic correction[68,70].

The concept of an optimal force level that produces the most efficient tooth movement without tissue damage or pain is discussed extensively in literature[6,11,12]. Force levels are proposed to directly correlate with tooth movement until exceeding a threshold where magnitudes adversely affect the periodontium without an increase in rate of tooth movement[58]. However, it is clinically impossible to measure the stress and strain of the PDL of a loaded human tooth in vivo[6,66]. As a result, literature typically focuses on the measurement of forces and moments generated by activated appliances[10,71].

An optimal force is light and continuous in nature, but its quantification is debated[58,71]. While orthodontic literature commonly describes forces in grams (gm), Newtons (N) is the technically correct unit measure of force[8]. A force as little as 2gm (approximately 2cN) has been shown to induce tooth movement[72], and orthodontic treatment applying up to 1000gm (1000cN) has been advocated[73]. Clinical tooth movement is also dependent on the desired type of movement and variability of an individual's morphology[11,71]. Proffit et al. suggested force magnitudes for each orthodontic movement based on his own interpretation of literature and clinical impressions: 35 - 60gm (35 - 60cN) for tipping, rotation and extrusion, 70 - 120gm (70 - 120cN) for translation, and 50 - 100gm (50 - 100cN) for root uprighting[7]. A systematic review concluded 50 - 100gm (50 - 100cN) of force is the optimal range for rate of orthodontic bodily movement, patient comfort and reduced side effects from the limited evidence available[10].

2.3 ORTHODONTIC BIOMECHANICAL PRINCIPLES

Translating the biological reaction of orthodontic force to the clinical perspective requires a knowledge of orthodontic biomechanics[51]. A core concept is the center of resistance (C_{res}), a geometric location through which a single force's line of action would produce pure bodily movement[51,57,74]. The C_{res} is positioned between one half to one third of the root length apical to the alveolar crest and depends on the tooth morphology such as the length and number of roots, and amount of alveolar bone support[51,75]. The location of the C_{res} can also be affected by applied forces at larger magnitudes, as the periodontium undergoes non-linear deformation[8,76,77].

Orthodontic forces are applied at the crown of the tooth because of anatomical limitations. Forces at the orthodontic bracket-archwire interface act at a distance away from the C_{res} and generate moments, the tendency to rotate an object[7]. The center of rotation (C_{rot}) is the point an object rotates around during movement. Manipulating forces and moments acting on a tooth moves the C_{rot} and create differential tooth movement, such as crown tipping, root torque, or bodily translation (Figure 2.1)[74]. Two equal forces of magnitude in opposite and parallel direction generate a couple, positioning the C_{rot} at the C_{res} for pure rotation. Altering the direction or magnitude of forces moves the C_{rot} closer to the root apex or tooth cusp for more crown tipping or root movement, respectively. If the C_{rot} is moved to infinity, bodily movement (translation) occurs.

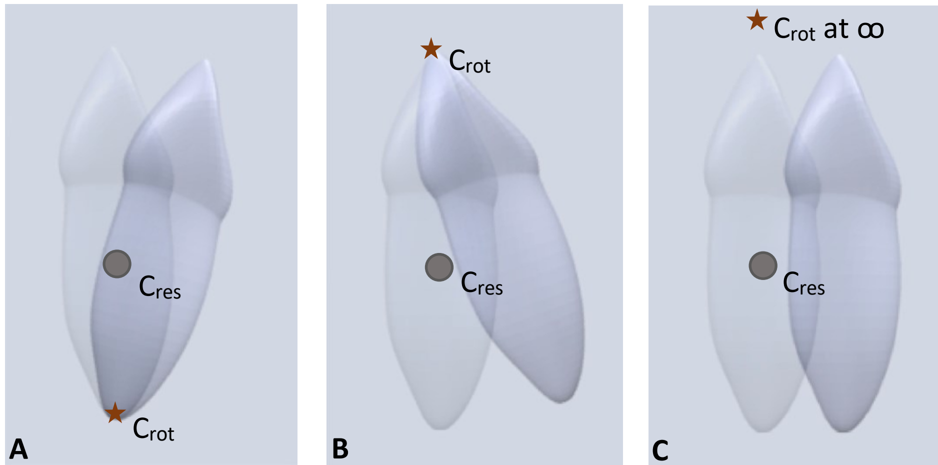

Figure 2.1 Differential tooth movement. **A,** Crown tipping. **B,** Root torque. **C,** Bodily translation

As a result, the knowledge of the acting forces and moments help predict the location of the C_{rot} relative to the C_{res} and the corresponding tooth movement[7]. Orthodontic forces and moments are manipulated with combinations of different archwires in size, shape, and material within the bracket slot at different positions[78]. Labial and lingual appliances inherently apply forces and moments to the tooth differently due to anatomical factors and appliance design[50]. Disparities between labial and lingual surface morphology change the relationship between force application and tooth movement. Labial surfaces generally have a gentle convexity, while the lingual surfaces of anterior teeth are concave with large individual variations[6,45,50]. The variance in inclination, curvature, marginal ridges, labial-lingual thickness, and cingulum also make orthodontic torque more difficult to control with lingual appliances[79–81].

The bracket location also affects the moments induced by forces applied at the bracket-archwire interface in relation to the C_{res}. The lingual bracket is closer labial-lingually than the labial bracket to the C_{res} of a maxillary incisor[81] (Figure 2.2), which Geron et al. calculated the difference to be 60%[50]. The same force load would, therefore, produce a smaller moment with lingual brackets. Tooth movement in all directions are implicated, and torque control is reported to be more difficult with lingual brackets[45,50].

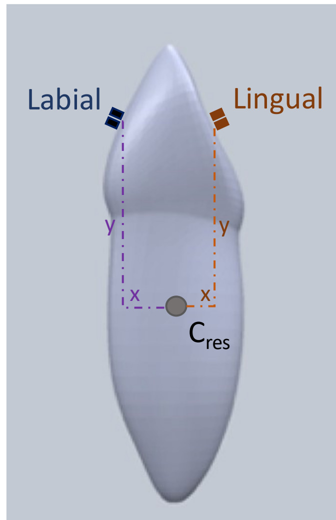

Figure 2.2 Bracket positions relative to the C_{res}.

The shape and size of labial and lingual archwire forms are different because of their corresponding bracket positions. Labial archwires are parabolic as the brackets follow a catenary curve from the occlusal view[82]. Lingual archwires must accommodate irregular tooth thicknesses along the lingual surface, especially between the canine and first premolar. Two archwire forms are commonly used with lingual appliances: straightwire (parabolic) or mushroom (Figure 2.3)[6,83]. A lingual straightwire is shorter in width and depth to the labial counterpart that is compensated by varying the thickness of the composite bond or bracket base[30]. Mushroom archwires keep the bracket closer to both the tooth surface and the C_{res} with a built-in step bend between the canine and first premolar[4,84]. The lingual archwires' inter-bracket distance is narrower along the lingual surface of anterior teeth thereby decreasing the activation range and force constancy and increasing the stiffness and load deflection rate[14,50]. As a result, lingual archwire forms are stiffer than its labial archwires during displacements in the labial-lingual and occlusal-gingival directions by a factor of 3.03, and labial-lingual rotations by a factor of 1.39[14], which translates to higher forces[15].

There is limited literature directly comparing effects between labial and lingual archwire forms to date. Lombardo et al. found the archwire stiffness to be similar between the two lingual archwire forms for both stainless steel and beta titanium archwires, but it can depend on the vertical position of the canine bracket[85]. Recent research measured statistical significant smaller moments on the first premolar when levelling a high canine with the lingual mushroom archwire compared to the lingual straightwire[84].

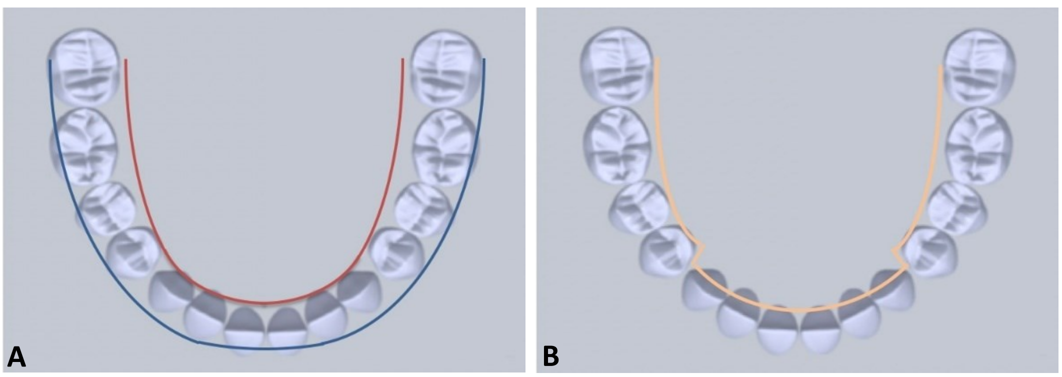

Figure 2.3 Archwire forms. **A.** Labial (blue) and lingual (red) straightwire. **B.** Lingual mushroom.

2.4 THE CURVE OF SPEE

The curve of Spee is defined as the arc of a curved plane tangent to the incisal edges and buccal cusps of the mandibular teeth in the sagittal plane (Figure 2.4)[21]. It was first described by Dr. Ferdinand Graf Spee in 1890 by locating the center and radius of the arc following the anterior border of the condyle and the occlusal surfaces of teeth[86]. In orthodontics, the severity is described in millimetres between the furthest cusp tip to the reference line of the mandibular occlusal plane[21,24].

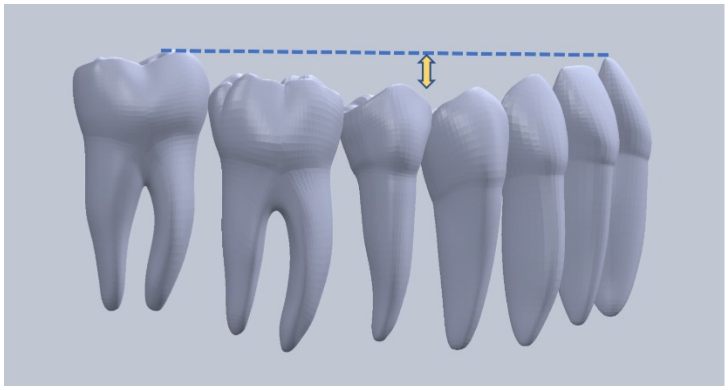

Figure 2.4 Severity of the curve of Spee (yellow arrow indicates the linear measurement between the further cusp tip and the reference mandibular occlusal plane).

The understanding of the curve of Spee etiology and morphology is limited[21,87]. The growth of orofacial structures, eruption of teeth, and development of the neuromuscular system have been proposed to contribute[88]. Marshall et al. analyzed dental casts and determined the curve of Spee was associated with the eruption of permanent teeth[21]. Initially, the curvature in the mixed dentition is minimal. The greatest increase in curve of Spee occurs with eruption of permanent mandibular first molars and central incisors and deepens further with mandibular second molars[89]. As mandibular teeth generally erupt six months prior to maxillary teeth, the lack of occlusal stops allows the permanent molars and incisors to over-erupt.

The curve of Spee has functional implications. Studies have shown a role in mastication with significant correlation between masseter muscle activity and chewing forces[88,90]. The curve of Spee also plays a significant role to establish a healthy and balanced occlusal scheme together with posterior cusp height, condylar inclination, and anterior guidance[89,91]. Furthermore, an inappropriate curve of Spee can lead to occlusal wear, premature fracture or failure of dental restorations, and temporomandibular joint disorders[91].

On the clinical side, levelling the curve of Spee to establish a flat occlusal plane is one of six fundamental orthodontic treatment goals [20]. It helps achieve proper intercuspation and is also a form of over-correction due to continual deepening of the curve of Spee during growth[20]. The depth of the curve of Spee is similar between left or right sides of the arch and sex[21,92]. It is more prevalent in Class II skeletal patterns (relative maxillary prognathism or mandibular retrognathism) primarily by eruption of posterior teeth compared to extrusion of anterior teeth exhibited in Class I (normal) and III (relative maxillary retrognathism or mandibular prognathism) skeletal patterns with a curve of Spee[93,94]. While the curve of Spee is associated with flatter mandibular plane angles[92], regression analysis showed weak correlation with craniofacial morphology overall[25]. It has the largest standard deviation of all cephalometric values[95] and is the biggest contributor to deep overbite[96,97].

Because a curved arch has a greater circumference than a flat arch, the relationship between arch length and curve of Spee has been investigated[24]. A popular concept accepted by practitioners is that the ratio of arch length needed to level every millimetre of curve of Spee is 1:1, but it has been disputed in the current literature[8]. This ratio has also been calculated to be to be 0.488 and 0.657 by separate studies[98,99]. Using more advanced measuring techniques, Braun et al. concluded that a curve of Spee depth of 4.5mm per side only increases arch circumference by 2mm[23]. In an in vitro study, Clifford et al. found exaggerating the amount of reverse curve of Spee incorporated into an archwire did not further increase the arch length either[30]. The ratio has also been described instead as non-linear and dependent on the archwire form used[24].

Clinical approaches correct the curve of Spee by extruding posterior teeth or intruding anterior teeth, depending on the treatment goals and philosophy[100,101]. Braun et al. suggested that the dental movement during levelling is more related to the mechanics used than the severity of curve of Spee[23]. Posterior dental extrusion will concurrently rotate the mandible downward and backward and increase the facial vertical dimension, beneficial for brachycephalic patients[23,96]. Another ideal indication is deep overbite since 1mm of posterior extrusion reduces overbite by 1.5 - 2.5mm[23,101]. This can be achieved by disarticulating with an anterior bite plate to allow posterior teeth to over-erupt[102–104] and may be more stable in a child with their growth's musculo-skeletal adaptation potential[105]. Segmented archwire mechanics can achieve similar posterior dental extrusion in adults or conversely, intrude anterior teeth, especially if there are concerns with pre-existing long face height[96], bone loss[106], or orthodontic instability[96].

Continuous archwires are the most common approach to correct the curve of Spee in contemporary orthodontic treatment due to its clinical ease of use[107]. The resultant dental movement is predominantly premolar extrusion and incisor flaring[92,102] with some contribution of incisor intrusion, and molar extrusion and uprighting[27,28,108]. However, the combination may vary based on a relationship between the vertical growth pattern and chewing forces[109,110]. Dolichofacial patients experience more posterior extrusion and uprighting, possibly due to decreased occlusal impact, while patients following a brachycephalic pattern has more incisor proclination and intrusion attributed to stronger masticatory musculature[28].

Orthodontic research has investigated the magnitude of incisor proclination due to associated concerns with gingival recession[111,112] and instability[101,113,114]. Incisor proclination also typically correlates with a decrease in inter-canine width[113,115]. These effects were corroborated in a study assessing levelling with flat and reverse curve of Spee labial archwires[30]. Interestingly, Shannon et al. found inter-canine width actually increased even with observed incisor proclination during curve of Spee correction, especially in extraction cases[92].

Curve of Spee levelling is considered stable with minimal relapse for both segmental and continuous archwire approaches[26,27,92,116]. The initial severity of curve of Spee is not correlated with the amount of relapse post treatment[26,116]. However, more relapse occurred with increased uprighting of the mandibular second molars[92].

Application of appropriate treatment mechanics requires a clear understanding of the forces and moments from an archwire during levelling[117]. For labial archwires, no statistical clinical differences were found based on material (stainless steel, multistranded steel, or nickel titanium)[117] nor dimension (0.016-inch versus 0.016-inch by 0.022-inch)[113]. And while archwire form is suggested to affect levelling curve of Spee[24], research of this relationship is sparse with no studies found directly comparing the impact from labial and lingual orthodontic appliances.

2.5 SYSTEMATIC REVIEWS COMPARING LABIAL AND LINGUAL APPLIANCES

There have been systematic reviews published comparing labial and lingual appliances. Ata-Ali et al. compared adverse effects and complications[118], and the included studies suggested lingual orthodontics is associated with increased pain, speech difficulties, and oral hygiene problems over labial systems. A second systematic review by the same group also assessed treatment outcomes[18]. The included clinical studies compared effects based on cephalometric records, and no statistically significant differences in final outcomes were found.

The systematic review by Papageorgiou et al. reported similar findings of higher speech impediment, eating difficulties, and overall oral discomfort with lingual brackets compared to labial brackets[2]. Lingual appliances had a distinct increase in inter-canine width and sagittal anchorage control and decreases in inter-molar width and interproximal reduction required.

Mistakidis et al. (2016)[17] published a systematic review that evaluated clinical accuracy and effectiveness, treatment duration, bond failures, periodontal health, and caries. Treatment accuracy and duration were similar between labial and lingual brackets, and there was less risk of decalficification with lingual brackets.

Every systematic review cautioned against any strong conclusions regarding labial and lingual appliance comparisons based on their findings because of the high risk of bias or low-quality nature of the available literature. The universal stumbling block are the inherent limitations in dental clinical trial design[119,120]. It is near impossible to expect blinding of either patient or clinician to the appliance used. Furthermore, obtaining large sample sizes of similar malocclusion to control multiple variables is difficult due to the length and cost of orthodontic treatment. Systematic reviews all mentioned the need for further research and have proposed matching an orthodontic approach to specific characteristics of a malocclusion (eg. levelling and alignment, space closure, intrusion) to obtain a stronger consensus[121].

2.6 METHODS OF INVESTIGATING ORTHODONTIC BIOMECHANICS

Contemporary orthodontics, using continuous archwires attached to multiple teeth, is considered an indeterminate system that is too complex to precisely calculate and predict the forces and moments involved[78]. The static equations of motion only allow for the determination of six unknown variables through Newton's Second Law, when in fact there are six unknowns (i.e., forces in all directions and moments in all directions) at each tooth. Simulation research helps study areas that would be difficult with in vivo trials such as biomechanical forces and moments. Studies have used various methods to analyze and measure orthodontic force loads exerted onto teeth and fall into two categories: in silico and in vitro.

Mathematical computer modeling via Finite Element Method (FEM)[122,123] has been well utilized for in silico orthodontic simulation[29]. The nodal forces and displacements determined from the simulations are used to determine stress and strain values within the structure resulting from orthodontically induced forces and moments. Comparisons between labial and lingual appliances used FEM to assess torque control[80], retraction of anterior teeth[124], molar mesialization[125], and biomechanical responses to incisors[126,127]. The utilization and interpretation is dependent on the model's assumptions of material properties, physical geometry, and load application[32,128]. For instance, changing the model assumption of PDL thickness can substantially affect the predicted tooth movement[129]. FEM also typically assumes orthodontic forces rigidly attached to teeth, when clinically, there is an interaction between archwires and brackets that can significantly change the load system[130].

In vitro methods, such as photo-elasticity, can simulate appliance driven biomechanics[131]. Anatomic tooth models bonded with brackets are set into a photo-elastic medium with polarized light passing through. Stress patterns appear on photographs as fringes or bands of colour that are subsequently analyzed. It has been used, for example, to evaluate levelling with reverse curve of Spee archwires[30] and space closure with springs[31] or retraction archwires[132,133]. However, comprehensive three-dimensional analysis is limited with photo-elasticity because of overlap on photographs[30,31].

The Calorific machine system, a typodont simulator developed by Rhee et al[36], is a similar concept. It comprises of a body housing temperature controls and electrothermodynamic teeth immersed in a medium representing alveolar bone, such as sticky wax. Heat conducted through the teeth softens the wax for tooth movement and photographs are taken of the resulting displacement. It was used to study effects of friction[36] and bracket size[134] during space closure and molar distalization with pendulum appliances[135]. This design was limited by the lack of a recognized standard for a medium to simulate the alveolar bone[36]. Like photo-elasticity, it was similarly unable to study torque of teeth due to visual overlap[134]. A modified version was created by Hung et al., the Heat Induction Typodont System (HITS), and again, the difficulty in facilitating lingual root torque was noted[38].

Appliance driven forces can alternatively be measured by load cells directly with apparatuses of various complexity. Single bracket-archwire set-ups have compared ligation methods[136,137], bracket designs[138,139], and archwires[139,140] for torque expression, friction, and force loads. Engaging an archwire between multiple brackets measured the stiffness of archwires[85] and forces from deflecting nickel titanium (NiTi) wires[141] or v-bends[142].

To simulate clinical treatment, load cells can be attached directly to targeted areas of a system akin to a dental arch. One method soldered brackets onto an archwire to study a new bracket system with sensors at three specific points[143]. Load cells have also been mounted to target teeth on a model to study bracket-archwire combinations[144] or effects of coil springs with mini-screws[145], different archwires[146], gable bends[147], and loop design[148,149] during space closure. Kuo et al. developed an apparatus that incorporated a maxillary dental arch to simulate first premolar space closure using tooth root sensors in the form of brass rings[37]. All these systems were limited to measuring forces and moments on a few specific teeth, not the whole system simultaneously.

The Orthodontic Measurement and Simulation System (OMSS), a mechanical in vitro simulator developed by Drescher et al., is able to simulate various malocclusions[35]. Sensors are attached to two teeth separated from a dental cast and placed on motor-driven positioning tables allowing three-dimensional movement. An integrated heat chamber maintains the temperature at 37°C to represent oral conditions, especially important when investigating thermal-dependent alloys such as NiTi archwires[150].

Biomechanical comparisons between lingual and labial appliances have used the OMSS. Studies found higher forces and lower moments with lingual brackets aligning displaced incisors regardless of inter-bracket design or archwire thickness[15,151]. A follow-up study by a group used the OMSS again to study initial alignment efficacy between labial and lingual brackets by moving the displaced teeth incrementally in response to force loads[152]. The higher force loads with lingual brackets conversely resulted in decreased alignment. The OMSS also compared the forces and moments on a lingually displaced incisor between lingual and labial brackets with copper NiTi archwires[151]. While the OMSS allows for three-dimensional forces and moments analysis with simulated malocclusions, it is limited to measuring two teeth at a time because of its design.

2.7 ORTHODONTIC SIMULATOR (OSIM)

The Orthodontic SIMulator (OSIM) is the first apparatus that could simultaneously measure three-dimensional forces and moments acting on all the teeth in a dental arch with precision, developed at the University of Alberta[39,153]. The dental arch is comprised of up to 14 teeth that are attached to multi-axis load cells. Horizontal and vertical micrometers can reposition each tooth labial-lingually and gingival-occlusally, allowing for a range of orthodontic simulation set-ups. The aluminum teeth, machined according to tooth anatomy and size, are bonded to orthodontic brackets. A heat chamber can be placed over the OSIM to replicate the oral cavity temperature. Forces and moments acting at each tooth are measured at the load cell and then transferred to an anatomical location of interest (e.g., C_{res} or bracket center) using a Jacobian transformation matrix.

The OSIM has investigated differences between elastic ligation and passive self ligation. With a simulated high canine, Fok et al. found elastic ligation expressed higher propagation of undesirable forces and moments throughout the dental arch due to increased resistance to sliding[154,155]. Seru et al. similarly concluded elastic ligation had higher forces and moments transmitted to additional to teeth with a lingually positioned maxillary incisor[40].

Interventions such as archwire size and anchorage have been investigated as well. Major et al. compared different sizes of copper NiTi archwires with a malpositioned high canine[156]. The study concluded that the diameter of copper NiTi archwires and its applied force had a non-linear relationship. Lee et al. found skeletal anchorage transmitted lesser forces on posterior teeth and higher vertical forces on anterior teeth compared to dental anchorage[41]. Overall, both anchorage types provided sufficient force to retract anterior teeth.

The OSIM has also been used to study lingual orthodontic mechanics. Owen et al. assessed load forces on a dental arch with a vertically displaced canine and a lingually positioned lateral incisor using lingual straightwires and mushroom archwires[84]. Lingual straightwires were concluded to have generally higher forces and moments, and the bend in the mushroom archwire significantly changed how forces were transmitted to the canine and first premolar. Space generation mechanics with lingual archwires were compared between crimpable stops and NiTi coil springs[157]. The study found greater forces and moments when using stops compared to coils, and the combination of stops and lingual straightwires exceeded optimal force values.

2.8 CLINICALLY SIGNIFICANT FORCES AND MOMENTS

It is important to relate quantification of forces and moments for clinical interpretation and application. Literature has not yet established a consensus on the minimum forces and moments required to cause tooth movement or root resorption. A recent systematic review concerning orthodontic force levels included 0.18N as the lowest force magnitude[10], and forces less than 0.2N did not have an effect on root resorption[158]. Andreasan et al. concluded only loads exceeding 15gm (0.15N) transmitted forces to the PDL[139]. Moments of 3Nmm have been proposed to produce appreciable tooth movement[138]. As a result, force and moment magnitudes above 0.2N and 3Nmm, respectively, will be considered clinically significant in the present study.

CHAPTER 3: IN VITRO MEASUREMENT OF THE INITIAL FORCES AND MOMENTS GENERATED FOR A CURVE OF SPEE MALOCCLUSION WITH LABIAL AND LINGUAL ARCHWIRE FORMS

3.1 INTRODUCTION

Orthodontic treatment corrects tooth misalignments, or malocclusions, to improve patient's dental health, psychologic well-being, and social perception[43]. Patients base successful treatment on how their teeth fit functionally and esthetically[159], but research has also shown the appliance's visual impact to be a primary factor[44]. Furthermore, a patient's decision for orthodontics is highly correlated with the psychosocial perception related to the influence of appearance while in treatment[160]. As a result, an increased demand for esthetic orthodontic treatment has been seen globally[3].

Orthodontic lingual brackets, introduced in the 1980s[4], provide a significant esthetic advantage by their placement on the lingual surface of teeth (ie., tongue- or palate-side) compared to labial brackets on the cheek-side[42]. It has similar overall patient satisfaction[49] and treatment outcomes[19,45] compared to the more common labial counterpart. Lingual treatment also has lower risk of caries[5] and decalcifications[161] but increased oral discomfort, speaking, and chewing dysfunction[118,162].

A fundamental orthodontic goal is to level the curve of Spee[20], the sagittal arc determined by the mandibular dental cusps and incisal edges[21]. It has a functional role in mastication forces[88,90], establishing balanced occlusion[21], and temporomandibular joint disorders[91]. A flat occlusal plane helps achieve ideal occlusal interdigitation[20], and the curve of Spee is the biggest contributor to deep overbites[96,97].

The curve of Spee's etiology is hypothesized to be a combination of orofacial structural growth and neuromuscular system development[88] and is more prevalent in skeletal Class II malocclusions (relative maxillary prognathism or mandibular retrognathism)[163]. The depth of the curve is similar across left and right sides of the arch and sex[92], worsening with the eruption of permanent mandibular molars and incisors[21]. The severity is classified by the largest distance of the farthest tooth to the reference line of the mandibular occlusal plane, defined by the distal buccal cusp of the most posterior molar and the incisal edge of the central incisor[21,24].

The specific dental movements for orthodontic correction are more dependent on clinical management[96,101] than the initial depth of the curve of Spee[23]. Orthodontic levelling is comprised of a combination of molar extrusion and uprighting, incisor intrusion and flaring, and premolar extrusion[27,28,92,102,108]. In contemporary orthodontics, correction is most commonly achieved with continuous archwires[101], and these movements are influenced by factors, such as the type of orthodontic appliance and archwire form used[24,30,50,101].

Dental alignment is based on orthodontic biomechanical principles[164]. They explain how forces and moments, a measure of the force's tendency to rotate an object, act on the tooth's center of resistance (C_{res}), the point through which a linear force produces bodily movement[6]. The relationship between the C_{res} and applied forces and moments ultimately determines whether torque (root movement), crown tipping, or bodily translation occur[57,75]. The magnitude of force loads is also important for optimal tooth movement[64,68] and the health of oral structures[10,64,68,69].

The biomechanics of orthodontic movement during curve of Spee levelling can impact treatment planning decisions. Increased posterior extrusion would be beneficial to increase the face height for brachyfacial patients, but it may be inappropriate for patients with a vertical growth pattern[23,96,101]. In addition, uprighting of mandibular second molars is associated with higher relapse potential[92]. There are conflicting reports on the amount of arch length required to level the curve of Spee[24,98,165] and the effects on inter-canine width[30,92,113]. Furthermore, incisor proclination is important to understand due to concerns with gingival recession[111,112] and instability[101,113,114]. Clinical applications of an increased knowledge base ultimately increase efficacy and avoid inappropriate forces, leading to lengthier treatment, root resorption, patient pain, and temporomandibular joint disorders[6,10–12].

Lingual and labial braces would have different forces and moments with distinct bracket locations[81] and archwire forms[4,6,166]. Lingual brackets are generally closer to the tooth's C_{res} than labial brackets[50], and as such, the same force creates a different moment around the C_{res}. Both appliances can use straight (parabolic) archwire forms with the lingual version narrower and smaller in size[6]. Lingual brackets can also use a mushroom archwire that includes a bend to accommodate the lingual anatomical step between the canine and first premolar[6,83,85]. Between the anterior teeth, lingual brackets are also closer together, which increases the force levels due to a larger archwire stiffness[14,15,50].

Orthodontic literature has assessed some aspects of orthodontic archwire design with curve of Spee levelling. The labial archwire form may change the amount of arch length required to level the curve of Spee[24]. A photo-elastic simulation found a minor decrease in inter-canine width with labial archwires, and incorporating a reverse curvature increased the stress pattern intensity around the molar and incisor apices[30]. Clinical studies compared labial archwires of different dimensions (0.016-inch and 0.016-inch by 0.022-inch)[113] and materials (stainless steel, multi-stranded steel, and nickel titanium)[117] and found no differences in incisor proclination. In a prospective clinical trial, reverse curve of Spee lingual mushroom archwires achieved incisor intrusion with minimal side effects[100]. However, no research to date has directly compared labial and lingual archwire forms to level the curve of Spee.

The purpose of this in vitro study was to understand the differences in initial forces and moments generated by labial straightwire, lingual straightwire, and lingual mushroom archwire forms engaged in a simulated curve of Spee malocclusion. Results between the different treatment options were compared to elucidate biomechanical differences that can be used to guide clinical treatment. The primary forces and moments of interest were the vertical (occlusal-gingival) forces, and the horizontal (labial-lingual) forces and moments. These were selected because teeth are vertically misaligned in a curve of Spee, which labial and lingual force applications would theoretically affect labial-lingual vectors[50].

3.2 MATERIALS AND METHODS

3.2.1 ORTHODONTIC SIMULATOR (OSIM)

The Orthodontic SIMulator (OSIM), developed at the University of Alberta, measures three-dimensional forces of individual teeth along an in vitro single dental arch with precision[39]. The experimental set-up consists of 14 teeth represented by additively manufactured stainless-steel posts with analogous dental crown anatomy and dimensions (Figure 3.1). Forces are measured by six-axis load cells (Nano17, ATI Industrial, Apex, NC, USA) rigidly attached to each tooth. Since the load cells are located away from the tooth, the measurements are transformed relative to the tooth's bracket location and the theoretical C_{res}, which are more clinically relevant. Coordinate systems for each tooth was converted using Jacobian transformation matrices from the load cell to approximated C_{res} locations obtained with a FARO arm (Faro Technologies, Lake Mary, Fla), as described in earlier research by Owen et al[84].

The measured output is analyzed using the computer programming environment MATLAB (MathWorks, Natick, Mass). The software packages developed in-house create a quick visual reference of the forces and moments measured for each tooth (Figure 3.2). A numerical read-out of the forces and moments in each direction is displayed. Data is exported to Microsoft Excel after each experiment for further analysis.

Figure 3.1 The Orthodontic SIMulator (OSIM) apparatus

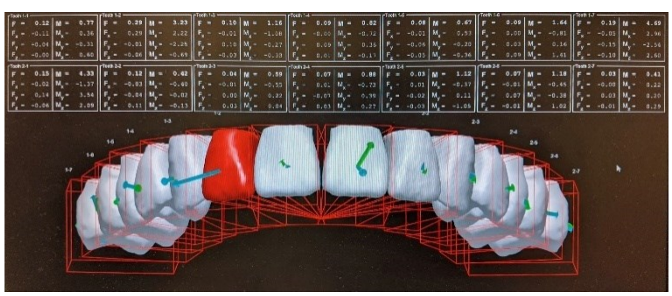

Figure 3.2 Visual reference of the forces and moments on the OSIM

3.2.2 ORTHODONTIC MATERIALS

Labial and lingual self-ligating 0.018-inch slot brackets (Carriere SLX, Cerum Ortho Organizers, Calgary, AB, Canada and In-Ovation L, Dentsply GAC, York, PA, USA, respectively) were bonded to the stainless-steel teeth using metal primer (Reliance Ortho Prod. Inc.), bonding agent (OrthoSolo, Ormco, Orange, CA), and composite resin (3M Unitek Transbond XT). To obtain the lingual and labial brackets with the same slot size (0.018-inch) and ligation method (self-ligating), they had to be acquired separately from different manufacturers.

The three mandibular archwire forms comprised of 0.016-inch by 0.022-inch stainless steel and were bent to a respective template for each group: labial straightwire, lingual straightwire, and lingual mushroom.

3.2.3 EXPERIMENTAL SETUP

Three treatment groups were compared in this study (Figure 3.3):

1. Labial straightwire
2. Lingual straightwire
3. Lingual mushroom

Figure 3.3 Experimental treatment groups. **A**, Labial straightwire. **B**, Lingual straightwire. **C**, Lingual mushroom.

The mechanical mandibular arch consisted of all teeth excluding third molars. The experiments started from the same initial passive position with the teeth levelled and aligned. The brackets were bonded to the approximate middle of the dental crown, using a bonding jig to allow passive fit of each archwire group. An archwire form template for each group was first established to which the jig and experimental archwires were fabricated.

When the brackets were bonded to the OSIM accordingly for each study group, the respective experimental trials were initiated. The same initial passive bracket position ensured consistent engagement of the archwires within each group. A new archwire was randomly selected from the same batch for each trial. Once engaged, a zeroing procedure was performed before testing to ensure an initial passive fit of the archwire in the brackets. The horizontal and vertical micrometers were adjusted for each load cell to measure less than 0.1N of force in all directions. This zero position of the teeth was established before initiating each trial.

The curve of Spee maximum position was established by moving the second premolar and canine 0.75mm and the first premolar 1.5mm gingival to the occlusal plane (Figure 3.4). While there can be various curve of Spee positions, this setup was chosen to establish a symmetric and parabolic curve of Spee from the sagittal view. The original intention was to have a 2mm curve of Spee to represent a depth of moderate severity that is typically seen clinically[92,93]. However, the forces and moments overloaded the load cells limit (25N and 250Nmm) of the OSIM during the pilot study, and the curve of Spee depth was therefore reduced to 1.5mm.

The OSIM was first bonded with lingual brackets to test the lingual straightwire. Subsequently, the labial brackets were bonded for the labial straightwire. The lingual brackets were then rebonded to the same teeth position for passive fit of the mushroom archwire. Brackets bonded for the mushroom archwires had thinner composite bases due to the archwire's closer adaptation to the lingual surfaces. The OSIM moved the teeth in 0.2mm increments, at which the average of 50 readings on all load cells for approximately one second was recorded.

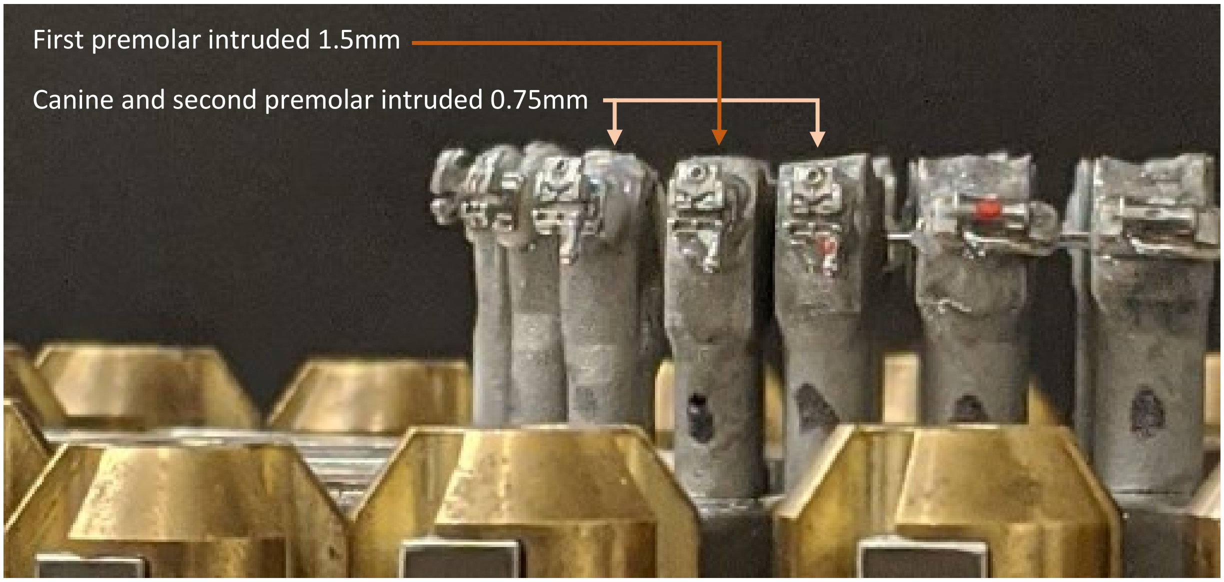

Figure 3.4 Simulated curve of Spee malocclusion

3.2.4 FORCE AND MOMENT MEASUREMENTS

Force and moment measurements relative to C_{res} were collected to the x-, y-, and z-axes (Figure 3.5):

1. Forces in the x-direction (F_x): mesial-distal forces
2. Forces in the y-direction (F_y): labial-lingual forces
3. Forces in the z-direction (F_z): occlusal-gingival forces
4. Moments in the x-direction (M_x): rotation causing crown/root movement in the labial-lingual direction
5. Moments in the y-direction (M_y): rotation causing crown/root movement in the mesial-distal direction

6. Moments in the z-direction (M_z): rotational movement around the long axis of the tooth

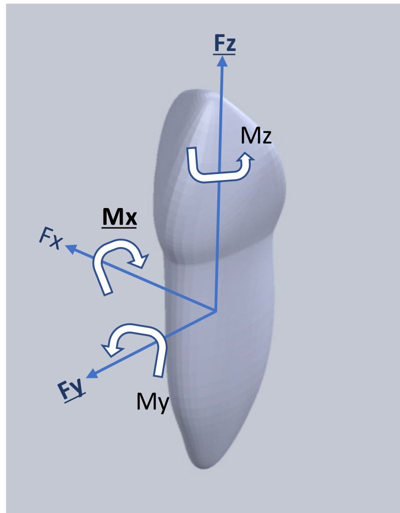

Figure 3.5 The force and moments coordinate system (main interests of this study are underlined).

The y- and z- axes were in the same direction for each tooth. However, the coordinate system of the OSIM orients the x-axis differently as it crosses the dental arch midline: positive indicates a distal direction on one side, and a mesial direction on the other side. As a result, data values for F_x, M_y, and M_z were adjusted to the same anatomical orientation of tooth movement for each tooth. The adjustments allowed for discussion of forces and moments in terms of clinical tooth movement directions. The force and moment values for the same tooth on the left and right side on the OSIM were then averaged for each archwire tested.

Using previous literature as a guide[10,138,139], forces above 0.2N and moments above 3Nmm were considered clinically significant in this study, the minimum threshold to induce tooth movement. While consensus has not yet been established, these thresholds have been accepted in orthodontic literature[84,157].

3.2.5 SAMPLE SIZE CALCULATION

A pilot study was completed to determine the necessary sample size by testing ten archwires in each group. The labial straightwire was the first group tested, with the first premolars intruded 2mm and the canines and second premolars intruded 1mm. However, this same set-up exceeded the force and moments limit of the load cells (25N and 250Nmm) with lingual archwires. As a result, the curve of Spee set-up was reduced to 1.5mm intrusion of the first premolars and 0.75mm of the canines and second premolars. Forces of 0.2N, and moments of 3Nmm were used as the minimal detection levels, determined to be relevant forces from previous literature[10,138,139]. As the labial straightwire pilot data had a different set-up, their values were not included in the sample size calculation. The forces and moments from the two lingual archwire forms were therefore used: F_z, F_y, and M_x on the canines, first and second premolars. The sample size (n) was calculated with the following formula, using a power of 1 – β = 0.90 and α = 0.05[167]:

$$n = \frac{\lambda}{\Delta}$$

$$\lambda = 12.66 \text{ when } 1 - \beta = 0.90 \text{ and } \alpha = 0.05$$

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

The calculated sample size (n) was 61 trials for each of the three experimental groups.

3.2.6 STATISTICAL ANALYSIS

Statistical analysis was completed with IBM SPSS version 21 software using a significance level of α = 0.05. The full trial data consisted of the forces and moments exerted onto the mandibular first and second molars, first and second premolars, canines, lateral incisors, and central incisors at the established experimental curve of Spee position. The average values of the right and left sides of the OSIM dental arch were used for each individual archwire tested. Prior to averaging, the data values of M_x were adjusted accordingly because of the OSIM's right hand coordinate system as mentioned previously. The main forces and moments of interest in this study were forces in the z-direction (F_z), forces in the y-direction (F_y), and moments in the x-direction (M_x), as shown in Figure 3.5, and therefore included for statistical analysis.

Two-way mixed multivariate analysis of variance (MANOVA) was selected to determine differences in the forces and moments on all teeth between archwire forms. The model assumptions of independence, normality, linearity, and equal covariance were assessed. Independence was met as each test used a different archwire and thus not related. Assumption testing was carried out using box plots for univariate normality, Mahalanobis distances for multivariate normality, scatterbox matrices for linearity, and Box's M test for equal covariance. The statistical significance was unaffected with and without the multivariate outliers found, and therefore, the reported analysis includes all data values. While linearity and equal covariance were violated, MANOVA is robust against these departures because of the study's larger sample sizes that are equal in number between groups. Greenhouse-Geisser correction was used for multivariate hypothesis statistical analysis, and Bonferonni correction was used for post-hoc pairwise comparisons.

3.2.7 STATISTICAL HYPOTHESES

There were three null statistical hypotheses for this study:

1. H_o: there are no differences in F_z, F_y, or M_x levels between the archwire forms.

   H_a: there is a difference in F_z, F_y, or M_x levels between the archwire forms.

2. H_o: there are no differences in F_z, F_y, or M_x levels between mandibular tooth position.

   H_a: there is a difference in F_z, F_y, or M_x levels between mandibular tooth position.

3. H_o: there are no interactions in F_z, F_y, or M_x levels between mandibular tooth position and archwire forms.

   H_a: there is an interaction in F_z, F_y, or M_x levels between mandibular tooth position and archwire forms.

3.3 RESULTS

Clinically significant F_z, F_y and M_x magnitudes are shown diagrammatically in Figure 3.6. The mean values and standard deviations of for each tooth are listed in Tables 3.1 – 3.3 and Figures 3.7 – 3.9. The two-way mixed MANOVA with Pillai's Trace F-test statistic indicated convincing evidence that F_z, F_y and M_x are dependent on a statistically significant interaction effect (p-value < 0.05) between mandibular tooth position and archwire form. The main effects of mandibular tooth position and archwire form were also statistically significant (p-value < 0.05). While the effects based on tooth position or archwire form alone could not be quantified because of the statistically significant interaction, there were overall trends observed between different factors.

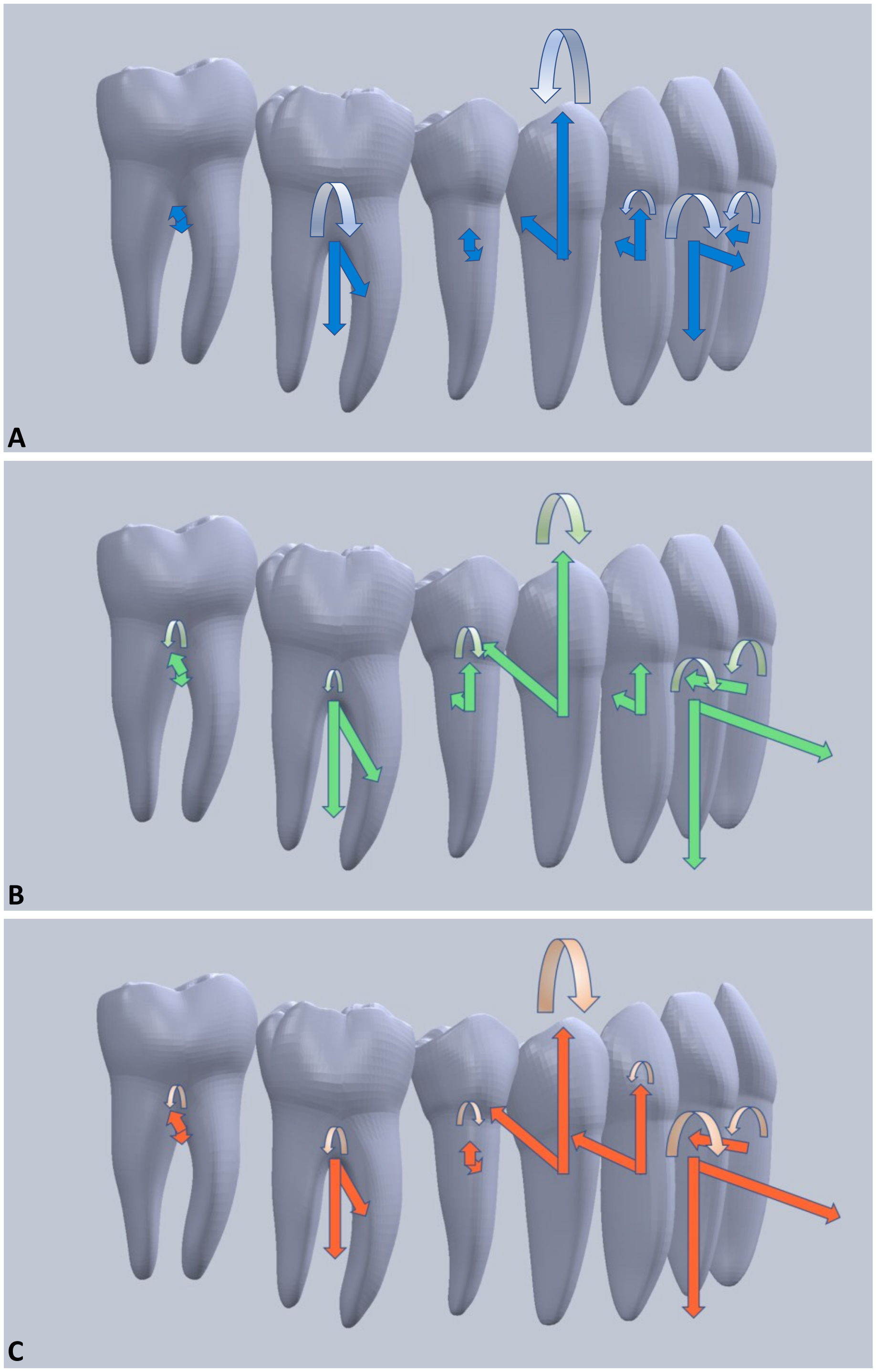

Figure 3.6 Visual depiction of the clinically significant forces and moments. **A**, Labial straightwire. **B**, Lingual straightwire. **C**, Lingual mushroom. The size of the vectors reflect relative magnitude but may not be exact to scale.

Table 3.1 Mean values of F_z ($\bar{x} \pm \sigma$) in N

Teeth \ Archwire form	Labial straightwire	Lingual straightwire	Lingual mushroom
Second molar	-0.27 ± 0.13	-0.54 ± 0.05	-0.59 ± 0.14
First molar	-3.00 ± 0.46	-3.74 ± 0.14	-3.24 ± 0.20
Second premolar	0.32 ± 0.17	1.51 ± 0.18	0.48 ± 0.45
First premolar	4.76 ± 0.69	5.36 ± 0.48	4.74 ± 0.67
Canine	1.37 ± 0.33	1.54 ± 0.32	2.89 ± 0.64
Lateral incisor	-3.18 ± 0.49	-5.44 ± 0.28	-5.18 ± 0.65
Central Incisor	-0.07 ± 0.08	0.00 ± 0.17	0.02 ± 0.31

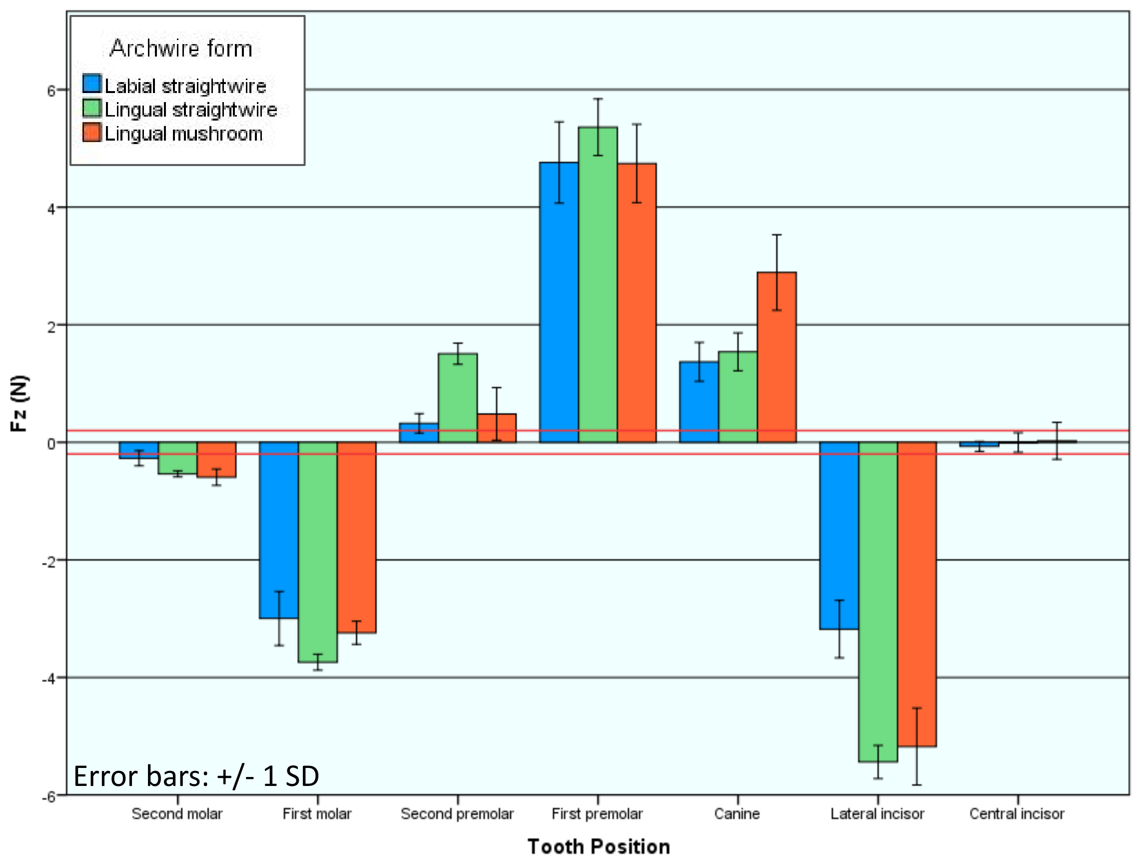

Figure 3.7 Mean values and standard deviation of F_z between archwire forms. Positive values and negative values indicate labial and lingual directions, respectively, and values between the red horizontal lines are clinically insignificant ($|F_z| < 0.2N$).

Table 3.2 Mean values of F_y ($\bar{x} \pm \sigma$) in N

Teeth \ Archwire form	Labial straightwire	Lingual straightwire	Lingual mushroom
Second molar	-0.36 ± 0.20	-0.77 ± 0.07	-0.57 ± 0.12
First molar	1.13 ± 0.25	2.81 ± 0.27	1.94 ± 0.23
Second premolar	0.22 ± 0.20	-0.63 ± 0.35	0.24 ± 0.80
First premolar	-1.97 ± 0.38	-3.35 ± 0.48	-3.06 ± 1.24
Canine	-0.58 ± 0.37	-0.81 ± 0.53	-2.33 ± 1.04
Lateral incisor	1.72 ± 0.39	4.81 ± 0.42	5.12 ± 1.10
Central Incisor	-0.75 ± 0.26	-2.03 ± 0.22	-1.94 ± 0.45

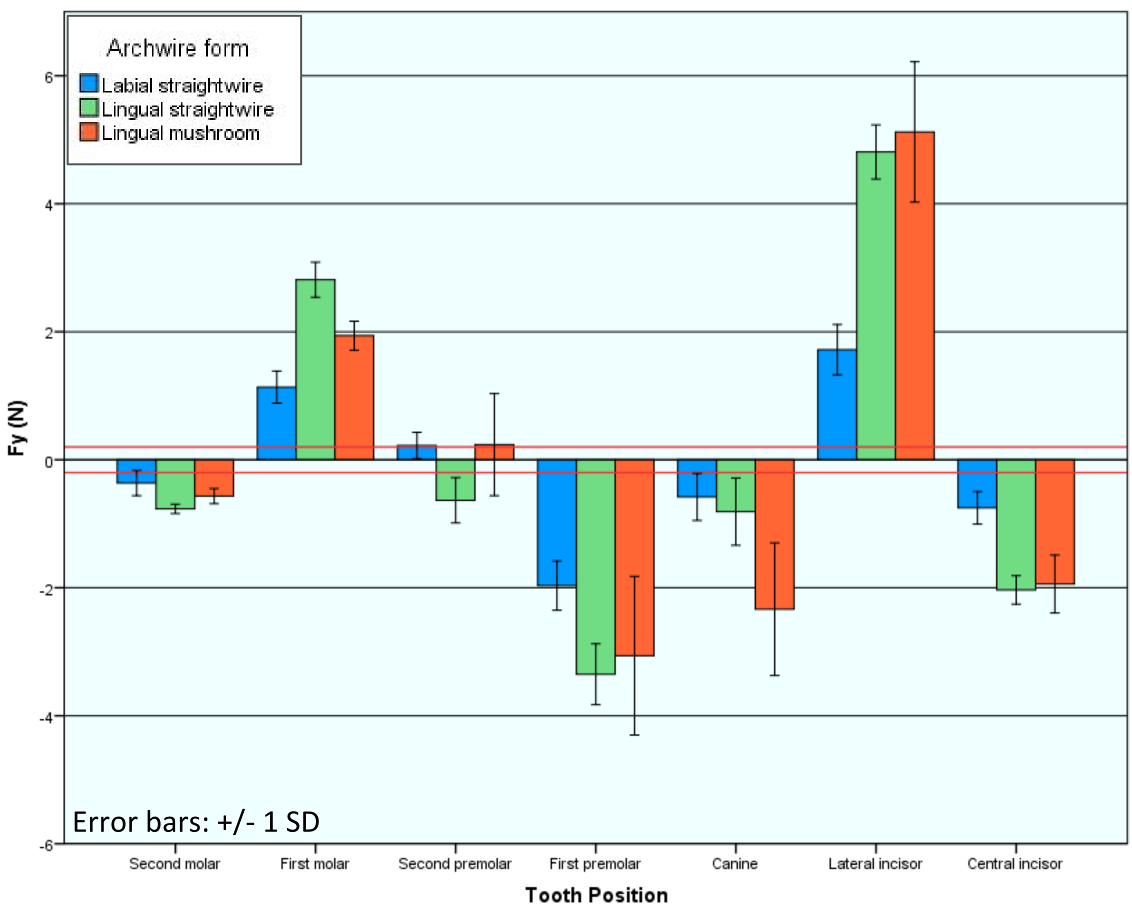

Figure 3.8 Mean values and standard deviation of F_y between archwire forms. Positive values and negative values indicate labial and lingual directions respectively, and values between the red horizontal lines are clinically insignificant ($|F_y| < 0.2N$).

Table 3.3 Mean values of M_x ($\bar{x} \pm \sigma$) in Nmm

Teeth \ Archwire form	Labial straightwire	Lingual straightwire	Lingual mushroom
Second molar	-0.09 ± 1.50	7.92 ± 1.75	8.05 ± 1.22
First molar	-32.03 ± 5.23	4.98 ± 1.28	9.45 ± 2.44
Second premolar	-0.21 ± 3.01	-13.09 ± 2.45	-9.83 ± 3.83
First premolar	42.45 ± 6.94	-20.57 ± 20.87	-39.07 ± 21.88
Canine	5.07 ± 4.71	0.90 ± 3.14	9.19 ± 8.09
Lateral incisor	-32.63 ± 6.13	-18.52 ± 2.96	-28.50 ± 7.10
Central Incisor	7.17 ± 2.91	18.06 ± 2.24	17.34 ± 3.96

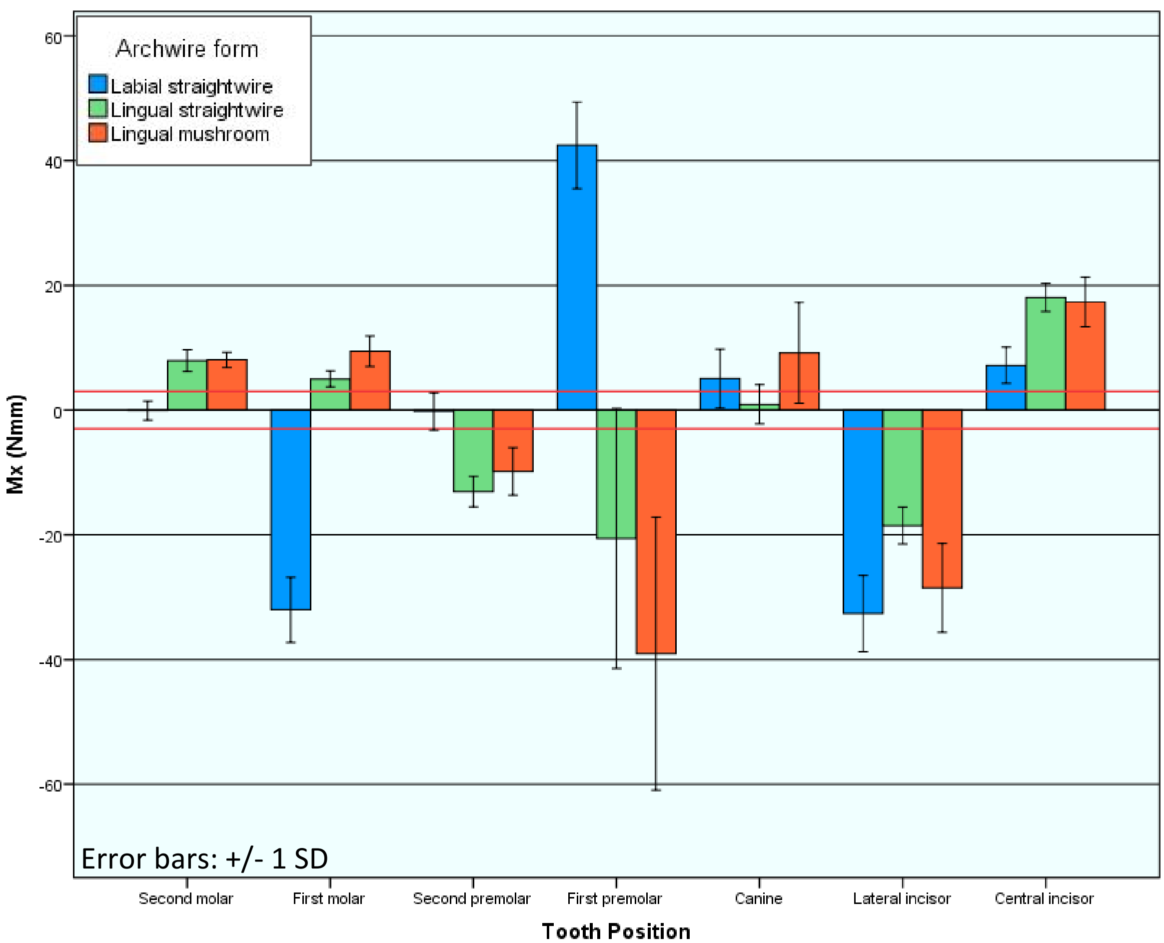

Figure 3.9 Mean values and standard deviation of M_x between archwire forms. Positive values and negative values indicate lingual and labial crown tipping, respectively, and values between the red horizontal lines are clinically insignificant ($|M_x| < 3$Nmm).

3.3.1 COMPARISON OF OCCLUSAL-GINGIVAL FORCES (F_Z)

The positive and negative F_z values represent vertical forces in the occlusal and gingival directions, respectively (Table 3.1 and Figure 3.7). Listed in order of decreasing magnitude, occlusally directed forces were exerted on the first premolar, canine, and second premolar, and gingivally directed forces on the lateral incisor, first molar, and second molar for all archwire forms.

3.3.2 COMPARING LABIAL-LINGUAL FORCES (F_Y)

The positive and negative F_Y values represent horizontal forces in the labial and lingual directions, respectively (Table 3.2 and Figure 3.8). For all groups, the lateral incisor received the greatest labial forces, followed by the first molar. F_Y was different for the second premolar; the two straightwires exerted minimal labial forces, and the lingual mushroom archwire exerted a slightly larger magnitude in the lingual direction. For the labial and lingual straightwires, the first premolar, canine, central incisor, and second molar received lingual forces in order of decreasing magnitude. The lingual mushroom archwire differed with the canine receiving slightly higher lingual forces than the central incisor.

3.3.3 COMPARING LABIAL-LINGUAL MOMENTS (M_x)

The positive and negative M_x value represent horizontal moments rotating the crown lingually and labially, respectively (Table 3.3 and Figure 3.9). The archwire groups exerted similar M_x vectors on each tooth position except the first molar and first premolar. The central incisor received lingual crown tipping moments, and the lateral incisor received labial crown tipping moments. The canine experienced lingual crown tipping lingually moments, but the magnitude was clinically insignificant with lingual straightwire (moments < 3Nmm). The second premolar and second molar recorded labial and lingual crown tipping moments, respectively, with both lingual archwires; the labial straightwire values were clinically insignificant on these two teeth. The first premolar recorded the largest M_x in both directions: labial crown tipping with the lingual straightwire and lingual crown tipping with the labial straightwire. The first premolar and first molar's M_x vectors were opposite between the labial straightwire and the two lingual archwire forms; labial straightwire exerted lingual crown tipping on the first premolar and labial crown tipping on the first molar, while the lingual straightwire and mushroom archwire exerted labial crown tipping on the first premolar and lingual crown tipping on the first molar.

3.3.4 COMPARING ARCHWIRE FORMS

Pairwise comparisons with Bonferonni adjustment between the archwire forms on each tooth are listed in Table 3.4, and the majority of the differences were statistically significant (p-value < 0.05).

Table 3.4 Pairwise comparisons between archwire forms on each tooth

Outcome	Tooth Position	Archwire form A	Archwire form B	Mean △(A-B) [95% C.I.]	p-value*
F_z (N)	Second molar	Labial SW	Lingual SW	0.27 [0.23, 0.31]	**< 0.0005**
		Labial SW	Lingual MW	0.32 [0.28, 0.36]	**< 0.0005**
		Lingual SW	Lingual MW	0.06 [0.02, 0.10]	**0.007**
	First molar	Labial SW	Lingual SW	0.74 [0.64, 0.85]	**< 0.0005**
		Labial SW	Lingual MW	0.24 [0.14, 0.35]	**< 0.0005**

		Lingual SW	Lingual MW	-0.50 [-0.61, -0.39]	**< 0.0005**
	Second premolar	Labial SW	Lingual SW	-1.19 [-1.29, -1.08]	**< 0.0005**
		Labial SW	Lingual MW	-0.16 [-0.27, -0.06]	**0.003**
		Lingual SW	Lingual MW	1.03 [0.92, 1.13]	**< 0.0005**
	First premolar	Labial SW	Lingual SW	-0.60 [-0.82, -0.38]	**< 0.0005**
		Labial SW	Lingual MW	0.02 [-0.21, 0.24]	0.887
		Lingual SW	Lingual MW	0.62 [0.40, 0.84]	**< 0.0005**
	Canine	Labial SW	Lingual SW	-0.17 [-0.34, -0.009]	**0.039**
		Labial SW	Lingual MW	-1.52 [-1.68, -1.36]	**< 0.0005**
		Lingual SW	Lingual MW	-1.35 [-1.51, -1.19]	**< 0.0005**
	Lateral incisor	Labial SW	Lingual SW	2.26 [2.08, 2.44]	**< 0.0005**
		Labial SW	Lingual MW	2.00 [1.82, 2.18]	**< 0.0005**
		Lingual SW	Lingual MW	-0.26 [-0.44, -0.08]	**0.004**
	Central incisor	Labial SW	Lingual SW	-0.07 [-0.14, 0.009]	0.086
		Labial SW	Lingual MW	-0.09 [-0.17, -0.02]	**0.015**
		Lingual SW	Lingual MW	-0.03 [-0.10, 0.05]	0.459
F_y (N)	Second molar	Labial SW	Lingual SW	0.40 [0.35, 0.45]	**< 0.0005**
		Labial SW	Lingual MW	0.21 [0.16, 0.26]	**< 0.0005**
		Lingual SW	Lingual MW	-0.20 [-0.25, -0.15]	**< 0.0005**
	First molar	Labial SW	Lingual SW	-1.68 [-1.77, -1.59]	**< 0.0005**
		Labial SW	Lingual MW	-0.80 [-0.89, -0.71]	**< 0.0005**
		Lingual SW	Lingual MW	0.87 [0.78, 0.96]	**< 0.0005**
	Second premolar	Labial SW	Lingual SW	0.86 [0.67, 1.04]	**< 0.0005**
		Labial SW	Lingual MW	-0.01 [-0.20, 0.17]	0.884
		Lingual SW	Lingual MW	-0.87 [-1.06, -0.69]	**< 0.0005**
	First premolar	Labial SW	Lingual SW	1.39 [1.10, 1.67]	**< 0.0005**
		Labial SW	Lingual MW	1.10 [0.81, 1.38]	**< 0.0005**
		Lingual SW	Lingual MW	-0.29 [-0.57, -0.004]	**0.047**

	Canine	Labial SW	Lingual SW	0.23 [-0.02, 0.48]	0.073
		Labial SW	Lingual MW	1.75 [1.50, 2.01]	**< 0.0005**
		Lingual SW	Lingual MW	1.52 [1.27, 1.78]	**< 0.0005**
	Lateral incisor	Labial SW	Lingual SW	-3.09 [-3.35, -2.83]	**< 0.0005**
		Labial SW	Lingual MW	-3.40 [-3.66, -3.15]	**< 0.0005**
		Lingual SW	Lingual MW	-0.31 [-0.57, -0.06]	**0.017**
	Central incisor	Labial SW	Lingual SW	1.28 [1.17, 1.40]	**< 0.0005**
		Labial SW	Lingual MW	1.19 [1.08, 1.31]	**< 0.0005**
		Lingual SW	Lingual MW	-0.09 [-0.21, 0.03]	0.122
M_x (Nmm)	Second molar	Labial SW	Lingual SW	-8.01 [-8.55, -7.47]	**< 0.0005**
		Labial SW	Lingual MW	-8.14 [-8.67, -7.60]	**< 0.0005**
		Lingual SW	Lingual MW	-0.13 [-0.67, 0.41]	0.637
	First molar	Labial SW	Lingual SW	-37.02 [-38.24, -35.80]	**< 0.0005**
		Labial SW	Lingual MW	-41.48 [-42.70, -40.26]	**< 0.0005**
		Lingual SW	Lingual MW	-4.47 [-5.69, -3.25]	**< 0.0005**
	Second premolar	Labial SW	Lingual SW	12.88 [11.75, 14.00]	**< 0.0005**
		Labial SW	Lingual MW	9.62 [8.49, 10.74]	**< 0.0005**
		Lingual SW	Lingual MW	-3.26 [-4.39, -2.14]	**< 0.0005**
	First premolar	Labial SW	Lingual SW	63.02 [56.62, 69.42]	**< 0.0005**
		Labial SW	Lingual MW	81.52 [75.12, 87.92]	**< 0.0005**
		Lingual SW	Lingual MW	18.50 [12.10, 24.90]	**< 0.0005**
	Canine	Labial SW	Lingual SW	4.17 [2.13, 6.20]	**< 0.0005**
		Labial SW	Lingual MW	-4.12 [-6.16, -2.09]	**< 0.0005**
		Lingual SW	Lingual MW	-8.29 [-10.33, -6.25]	**< 0.0005**
	Lateral incisor	Labial SW	Lingual SW	-14.10 [-16.13, -12.07]	**< 0.0005**
		Labial SW	Lingual MW	-4.13 [-6.16, -2.10]	**< 0.0005**
		Lingual SW	Lingual MW	9.98 [7.95, 12.01]	**< 0.0005**
		Labial SW	Lingual SW	-10.89 [-12.01, -9.77]	**< 0.0005**

	Central incisor	Labial SW	Lingual MW	-10.17 [-11.28, -9.05]	**< 0.0005**
		Lingual SW	Lingual MW	0.72 [-0.39, 1.84]	0.20

*Bolded values indicate statistically significant values

The three archwire form groups exerted F_z and F_y generally similar in direction at different magnitudes on each tooth position. For F_z, the canine, first premolar, and second premolar received occlusal vectors, and the lateral incisor, first molar, and second molar received gingival vectors. For F_y, the archwire forms all exerted labial forces on the lateral incisor and first molar and lingual vectors on the central incisor, canine, first premolar, and second molar. The second premolar was the only tooth where any force had a different direction based on archwire form; labial vectors were recorded with the labial straightwire and lingual mushroom archwire, while the lingual straightwire exerted lingual vectors.

The labial straightwire exerted forces with the lowest magnitude for all tooth positions. The lingual straightwire exerted the highest vertical forces except on the canine and central incisor and the highest horizontal forces except on the lateral incisor and canine. The order of force magnitude between tooth positions was similar across the groups.

The direction of M_x was similar between the two lingual archwire forms that differed to the labial straightwire. The two lingual straightwires exerted lingual crown tipping on the central incisor, canine, first molar, and second molar and labial crown tipping on the lateral incisor, first premolar, and second premolar. The labial straightwire exerted opposite M_x directions on the first premolar and first molar.

The labial straightwire exerted the largest absolute M_x magnitudes on the lateral incisor, first premolar, and first molar. Of the lingual archwire forms, the mushroom variant was larger on all tooth positions except the central incisor and second premolar. On the first premolar, the labial straightwire exerted the greatest overall lingual crown tipping, and both lingual archwires forms exerted labial crown tipping. The standard deviations of the two lingual archwire forms on the first premolar were significantly larger than any other measured outcome variable.

3.4 DISCUSSION

Initial forces and moments on mandibular teeth in a curve of Spee malocclusion were compared between three archwire forms used by labial and lingual orthodontic appliances: labial straightwire, lingual straightwire, and lingual mushroom archwire. The primary forces and moments of interest were the vertical forces in the occlusal-gingival direction (F_z), horizontal forces in the labial-lingual direction (F_y), and horizontal moments in the labial-lingual direction (M_x). The OSIM allowed for simultaneous measurement of the acting three-dimensional forces and moments of each tooth within a single dental arch (excluding third molars), which are otherwise impossible to calculate and predict with continuous archwires[7]. The statistical analysis determined the vertical forces and horizontal forces and moments were dependent on the relationship between the archwire form and tooth position, and similarities and differences based on archwire form and tooth position were observed.

3.4.1 SIMILARITIES BETWEEN ARCHWIRE FORMS

The mandibular teeth received the same direction of occlusal-gingival forces regardless of archwire form. Teeth below the reference occlusal plane received occlusal forces at magnitudes relative to the distance of its displacement; the first premolar, the most intruded, received the greatest extrusive forces, followed by the canine and second premolar. These values suggest that each archwire form exerts appropriate forces in the occlusal direction on these teeth to achieve the specific clinical goal of levelling the curve of Spee.

Each archwire form exerted the greatest gingival forces on the lateral incisor, which may be representative of the expected intrusive movement during curve of Spee levelling[27,28,108]. Research has indicated larger magnitudes increase the incidence and severity of root resorption but not the rate of movement[168–172]; however, there is no established consensus regarding the force threshold that would induce said damage. Based on expert opinion and low level of evidence, 10 - 25gm (approximately 10 - 25cN) is proposed to be the optimal range for intrusive forces on a mandibular incisor[7,96]. These suggested thresholds are exceeded by the recorded intrusive forces on the lateral incisor. However, it is important to highlight that the rigid connectors within the OSIM do not account for biological PDL compliance that would reduce this initial loading. Intrusion is the most common tooth movement associated with orthodontic root resorption[171,173]. The lateral incisor also received labial crown tipping (lingual root tipping) moments, another strong predictor for root resorption[174]. Incisors already carry a higher risk for root resorption with roots that are smaller in size and conical in shape[7]. As a result, clinicians may need to closely monitor lateral incisors for root resorption during curve of Spee levelling for any archwire form.

Like the first molar, the lateral incisor received gingival and labial force vectors, but at larger magnitudes. However, the lateral incisor did not have different labial-lingual moment directions between labial and lingual archwire forms, recording labial crown tipping. All archwires load brackets that are occlusal to a tooth's C_{res}. The significantly larger labial forces were likely the main factor behind the labial crown tipping moments recorded for all groups. A horizontal force, compared to a vertical force of the same magnitude, creates larger moments since the vector has a greater relative horizontal distance to the C_{res} (Figure 3.10). As a result, the extreme labial forces on the lateral incisor predominantly resulted in the labial crown tipping moments for all groups.

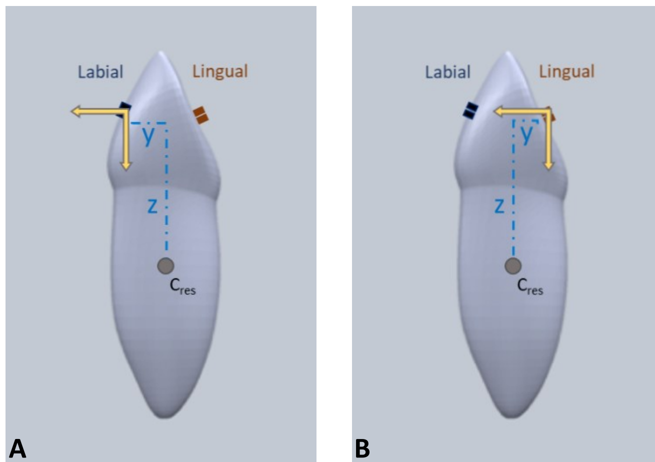

Figure 3.10 Comparison of the distances from horizontal forces (y) and vertical forces (z) to the tooth's C_{res}. **A**, Labial load position. **B**, Lingual load position.

3.4.2 DIFFERENCES BETWEEN ARCHWIRE FORMS

Between the archwire forms, the force magnitudes for horizontal and vertical forces at each tooth position was the lowest with labial archwires. Lower forces with labial appliances were also found in an in vitro study aligning a single incisor[15]. These lower magnitudes were likely because of the decreased archwire stiffness associated with larger inter-bracket distances in labial appliances compared to lingual appliances[14] and may reduce the risk of root resorption[67,171,175]. As a result, labial archwires may be more indicated in cases where root resorption is more debilitating, such as patients with poor periodontal support[7], or treatment with higher risk of root resorption, such as longer treatment durations or involving orthodontic space closure[6].

The directions of horizontal moments on the teeth were the same between the two lingual archwire forms. Labial archwires exerted opposite directions of labial-lingual moments on the first premolar and first molar. The contrasts are likely due to the large vertical forces and the different load positions with labial and lingual appliances relative to the C_{res}. Occlusally directed forces would naturally generate lingual crown tipping with labial brackets and labial crown tipping with lingual brackets. Similarly, gingival forces would create labial crown tipping with labial brackets and lingual crown tipping with lingual brackets. The magnitudes of labial-lingual moments on the first molar from the lingual archwires were not as large compared to the labial straightwire. The moments associated with labial forces observed with lingual archwire forms diminished the overall lingual crown tipping moments from the larger gingival forces.

The archwire form may have implications in the transverse dimension if the assumption that the recorded forces and moments vectors will correspond directly to the clinical tooth movement is made. Of the posterior teeth, the first premolar received the largest lingual and occlusal forces, and the first molar received the largest labial and gingival forces regardless of archwire form. With a labial bracket position, the horizontal moment vectors associated with those forces were lingual crown tipping on the first premolar and labial crown tipping on the first molar. As a result, the directions of these horizontal moments were additive to the lingual forces on the first premolar and labial forces on the first molar with labial archwires, moving the dental crowns in the same direction. Lingual archwire forms, in contrast, had antagonistic labial-lingual force and moment directions on the crowns of the first premolar and first molar; the first premolar experienced lingual forces with labial crown tipping, and the first molar experienced labial forces with lingual crown tipping. The larger net directional loads on the crown portion of the first premolar and first molar with a labial archwire form may result in more apparent transverse changes on posterior teeth when compared to both lingual archwire forms (Figures 3.11 and 3.12). Clinicians using labial archwires may need to closely monitor for narrowing at the first premolars and widening of the first molars when levelling the curve of Spee and adjust the archwire accordingly.

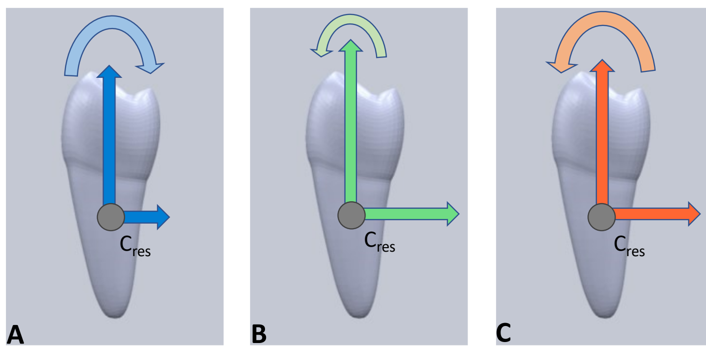

Figure 3.11 Forces and moments acting on the first premolar's C_{res}. **A**, Labial straightwire. **B**, Lingual straightwire. **C**, Lingual mushroom.

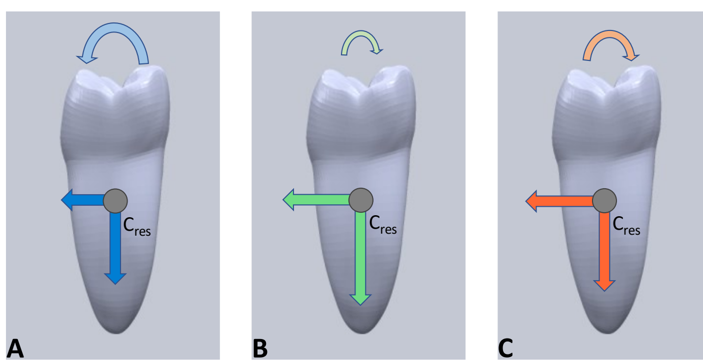

Figure 3.12 Forces and moments acting on the first molar's C_{res}. **A**, Labial straightwire. **B**, Lingual straightwire. **C**, Lingual mushroom.

With respect to the first premolar, the standard deviations of labial-lingual moments were considerably larger with the two lingual archwire forms than the labial archwires. This may signify better predictability of the labial-lingual inclination of the first premolar with labial archwire and decreased control with lingual archwires. Previous research similarly suggested decreased torque control during vertical movements with lingual appliances[50]. The root inclination of the first premolars may require close attention during lingual orthodontic treatment to be managed clinically such as a third order bend in the lingual archwire.

Assessment of the labial-lingual moments exerted on the teeth requires consideration of the potential bracket-archwire interaction. In this study, the 0.016-inch by 0.022-inch archwire could theoretically rotate up to 6.7° before engaging the walls within the 0.018-inch bracket slot to generate a torsional moment[176]. The magnitude would increase with larger archwires relative to the bracket slot size[177]. However, the labial-lingual moments recorded in this study seem to primarily derive from the acting horizontal and vertical forces that originate away from the C_{res} at the bracket-archwire interface. While archwire dimensions certainly impact torque expression at the individual bracket-archwire interface[177], a clinical study found no differences between round and rectangular labial archwires on incisor proclination during levelling[113]. Future simulation studies comparing different archwire sizes to further investigate its effect at the bracket-archwire interactions of a dental arch with a curve of Spee malocclusion are recommended.

3.4.3 CLINICAL SIGNIFICANCE

This study determined statistically significant differences in the forces and moments between labial and lingual archwire forms on mandibular teeth in a curve of Spee malocclusion. The forces and moments recorded may have clinical implications as the values observed were generally above the clinically relevant magnitudes chosen (forces > 0.2N, moments > 3Nmm). These findings may facilitate clinical understanding and treatment applications.

The three archwire forms commonly used with labial and lingual orthodontics exerted a similar pattern of initial vertical and horizontal forces on the mandibular teeth with a curve of Spee. The vertical force vectors were appropriate to level the curve of Spee; teeth positioned below the occlusal plane received occlusal forces at magnitudes relative to their displacement.

With respect to labial-lingual moments, differences between archwire forms may have clinical considerations. The labial straightwire exerted crown tipping moments that would exacerbate the horizontal forces on the crown portion of the first premolar and first molar, while lingual archwire forms exerted horizontal moments that would tip these crowns opposite to the labial-lingual forces. As a result, the crowns of posterior teeth may have increased transverse effects with labial archwires, seen clinically as narrowing sbetween the first premolars and widening between the first molars. On the other hand, lingual archwire forms may have unpredictable torque control on the first premolars; the standard deviations of their horizontal moments recorded with lingual straightwires and mushroom archwires were substantially large.

With forces above the clinically relevant threshold, it is equally important to discuss potential excessive magnitudes that could cause harm. Research has shown root resorption to be positively correlated to force magnitudes[171,172,178]. Labial archwire forms exerted the lowest force magnitudes on all teeth and therefore, may be more biologically acceptable. Lingual archwire forms may warrant treatment considerations during the levelling phase to prevent adverse side effects, such as using smaller dimensional or more flexible archwires. Special attention to the lateral incisors with any archwire form during levelling may be required since significant labial and gingival forces were recorded in this study. Lateral incisors are already at high risk for root resorption with conical roots that are smaller in size[7]. Furthermore, the gingival forces and horizontal moments seen on the lateral incisor may represent intrusion and lingual root tipping, respectively, tooth movements most commonly associated with root resorption[171,173,174].

However, orthodontic literature has yet to establish a consensus on the upper limit of applied forces without adverse effects. A recent systematic review suggested forces above 100gm (100cN) increase the risks of patient discomfort and root resorption[10]. Proffit et al. proposed 120gm (120 cN) forces to be the upper bound of optimal force levels[7]. While many of the forces recorded were above these suggested optimal force levels, clinical PDL compliance, not replicated by the rigid connectors used in this simulation, would likely reduce these magnitudes. This should be considered with any interpretation of the values in this study.

3.5 CONCLUSION

The present study indicated statistically significant differences in the initial forces and moments of interest (F_z, F_y and M_x) dependent on the three labial and lingual archwire forms and the mandibular tooth position (central incisor, lateral incisor, canine, first premolar, second premolar, first molar and second molar) with a curve of Spee malposition. Many of the forces and moments exerted were clinically relevant (forces > 0.2N, moments > 3Nmm). As a result, these findings improve orthodontic biomechanical understanding and may provide clinical treatment applications.

CHAPTER 4: FINAL DISCUSSION

4.1 GENERAL DISCUSSION

Orthodontic treatment applies biomechanical principles of forces and moments at the bracket-archwire interface to create differential tooth movement to align teeth. An increased understanding would benefit treatment by improving predictability of tooth movement and reducing undesirable side effects with improved force systems and prevent adverse effects, such as root resorption and patient pain from excessive forces[8].

This present study aimed to compare the initial forces and moments generated on mandibular teeth between three labial and lingual archwire forms (labial straightwire, lingual straightwire and lingual mushroom) in a simulated curve of Spee malocclusion. Labial and lingual appliances inherently have biomechanical implications due to the different appliance locations and corresponding arch forms used[6]. No literature to date has directly compared the effects of labial and lingual archwire forms to achieve a flat curve of Spee, a key orthodontic treatment goal[20].

The Orthodontic SIMulator (OSIM), an in-vitro apparatus, was used to measure the three-dimensional forces and moments of each mandibular tooth with the first premolar intruded 0.75mm, and the canine and second premolars intruded 1.5mm for the study's established curve of Spee malposition. The results determined that the vertical (occlusal-gingival) forces and horizontal (labial-lingual) forces and moments had statistically significant differences dependent on the archwire form and tooth position. General similarities and differences were observed between the archwire forms.

Horizontal and vertical forces exerted onto individual teeth were similar in direction between archwire forms. The archwire forms exerted initial occlusally-directed forces on to teeth that were appropriate for curve of Spee levelling and at magnitudes that were relative to the tooth's vertical displacement; the first premolar, more intruded than the second premolar and canine, received greater loads. The lateral incisor received the largest reciprocal gingival forces with labial crown tipping moments from each archwire form as well. These vectors are representative of intrusion and lingual root torque, dental movements associated with increased risk of resorption especially at larger magnitudes. The lateral incisor is already at higher risk of root resorption due to its smaller and conical roots, and as a result, close monitoring of these teeth during curve of Spee levelling may be warranted, regardless of the archwire form used.

This study also found differences between labial and lingual archwire forms. The standard deviation of the labial-lingual moments on the first premolar was much larger with both lingual archwires. This observation would correlate with previous research that cited decreased torque control during vertical movements with lingual appliances[13]. The first premolar and first molar's horizontal forces and moments directions were additive with labial archwires but opposite in direction with lingual archwires. If the initial forces and moments are indicative of the resulting tooth movement, increased transverse changes may result with labial archwires during levelling. Labial archwires consistently exerted the lowest force magnitude at each tooth position, lowering the risk of root resorption compared to lingual archwires.

4.2 STUDY LIMITATIONS

Limitations of this study is due to the in-vitro nature of this study. The methodology did not replicate biological considerations such as saliva, periodontal ligament (PDL), pressure from soft tissues, masticatory forces, and interproximal contacts. The role of saliva is debated, shown to both increase and decrease friction, and furthermore, lubrication may not be a factor with heavier forces[179–181]. The rigid connectors of the OSIM does not replicate PDL compliance, which likely decrease the initial force magnitudes recorded in a clinical scenario. A study found inclusion of a PDL model simulation had a statistically significant decrease of 1.6Nmm on torquing moments but only at lower angles[182]; however, this difference was deemed not as clinically significant at magnitudes greater than 5Nmm, relevant to the moments seen in this study. Abnormal pressure from the tongue or lips (such as a tumor or functional habit) can influence tooth movement, but the normal intermittent short duration pressure from soft tissues are unlikely to influence tooth position[7]. Masticatory forces are related to craniofacial morphology, and studies have suggested it can influence the vertical position of teeth[28,109]. Perturbations from masticatory forces may also play a role with respect to friction, but its effect is still debated[183,184]. Friction and pressure from interproximal contacts would potentially impact force propagation and resulting force loads to other teeth or the periodontium. The OSIM did not include interproximal tooth contacts to allow an initial zero position of the mechanical teeth prior to archwire insertion. This zero position was necessary to establish the same reference set-up for the experimental groups to allow for direct comparisons.

The purpose of this study was to investigate the initial forces and moments exerted onto teeth in a curve of Spee malposition between labial and lingual archwire forms. The recorded magnitudes represent the force systems at this initial curve of Spee position and not the resultant tooth movement. Application and interpretation of the results should certainly consider the limitations given the in vitro observational nature of this study, which may impact the reported magnitudes. As the same methodology was applied strictly to each experimental group, however, the comparisons are still relevant and provide insight into orthodontic biomechanical systems.

4.3 FUTURE RECOMMENDATIONS

There is currently minimal research on labial and lingual biomechanical comparisons. This study compared labial and lingual archwire forms with 0.016-inch by 0.022-inch stainless steel to level the curve of Spee. It may be interesting to study archwire forms made of different materials and dimensions. Future studies can also compare effects with a reverse curve of Spee incorporated into an archwire. The curve of Spee model was arbitrarily set with the first premolar, canine and second premolar intruded 1.5mm, 0.75mm, and 0.75mm, respectively. There would be value in assessing different curve of Spee positions and severities. Future research simulating other malocclusions to compare labial and lingual appliances would additionally be beneficial that may yield relevant clinical applications.

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APPENDIX

A.1 INTERACTION BETWEEN TOOTH POSITION AND ARCH FORM

Profile plots were used to assess the relationship between tooth position and arch form groups regarding F_z, F_y, and M_x (Figures A.1 – A.3). The observed non-parallelism suggests that there is convincing evidence there is a significant interaction between the tooth position and arch form used, rejecting the null hypothesis H_{o3}. This is corroborated by Pillai's Trace F-test statistic: $F(36, 328) = 341.85$, $p < 0.0005$, Pillai's trace = 1.95, partial $\eta 2 = .97$ (Appendix, Table B.1).

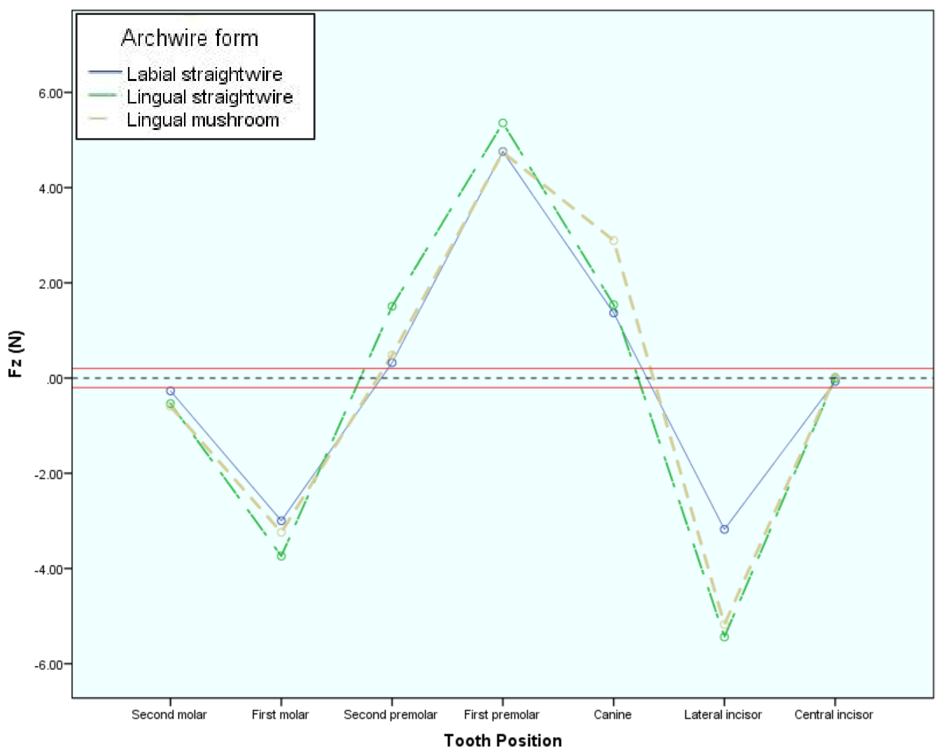

Figure A.1 F_z profile plot between tooth position and archwire form. Values between the red horizontal lines are clinically insignificant ($|F_z| < 0.2N$).

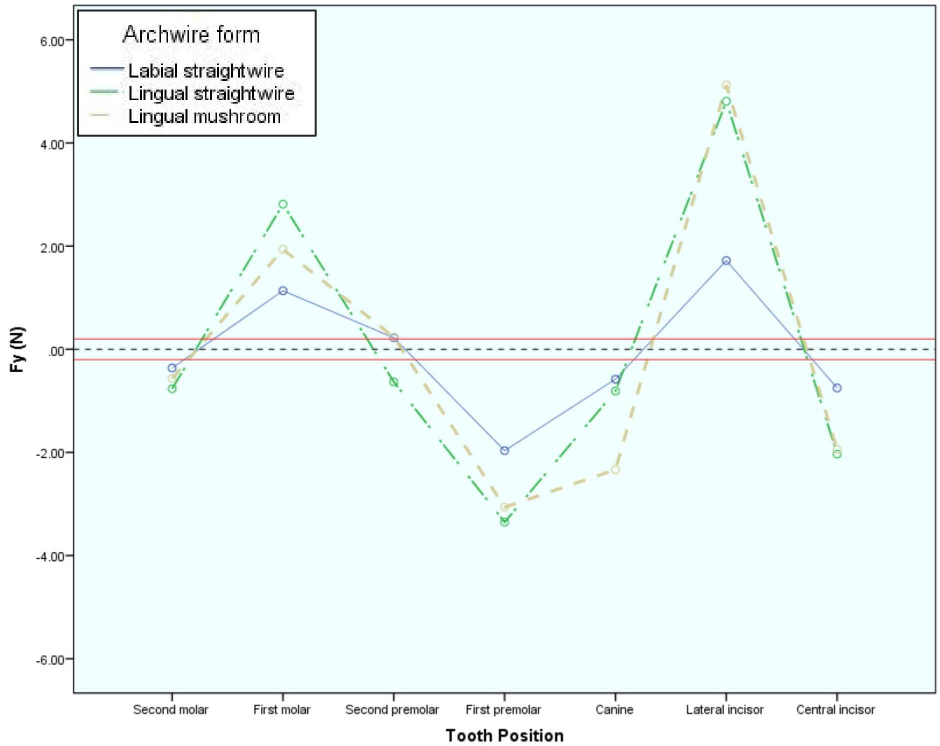

Figure A.2 F_y profile plot between tooth position and archwire form. Values between the red horizontal lines are clinically insignificant ($|F_y| < 0.2N$).

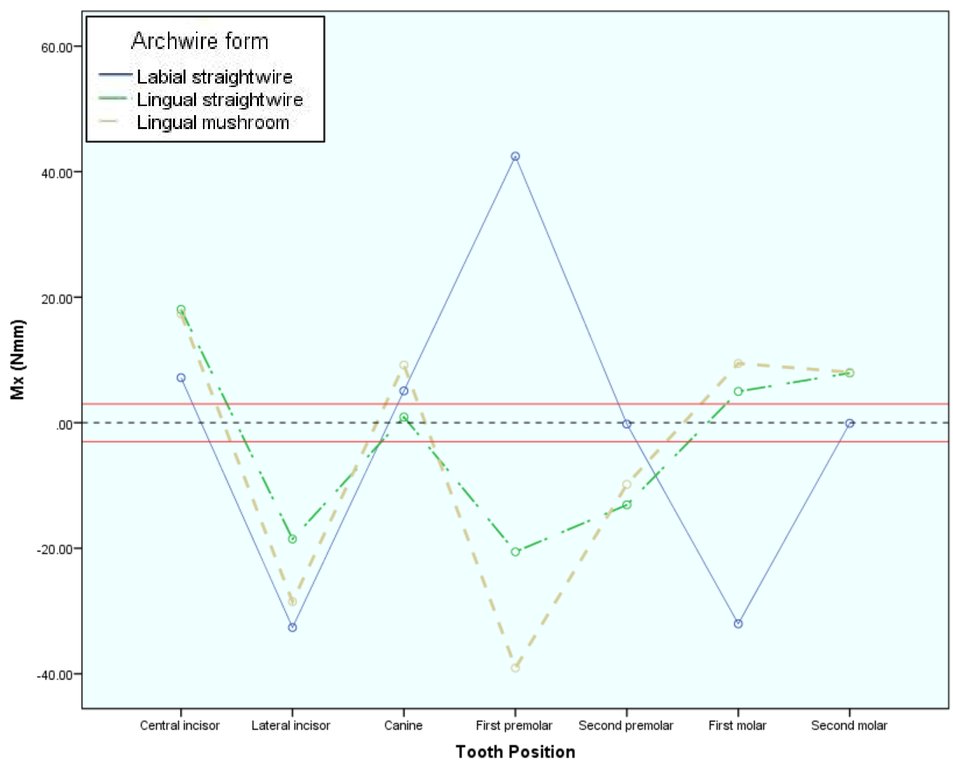

Figure A.3 M_x profile plot between tooth position and archwire form. Values between the red horizontal lines are clinically insignificant ($|M_x| < 3Nmm$).

B.1 ADDITIONAL STATISTICAL ANALYSES FIGURES AND TABLES

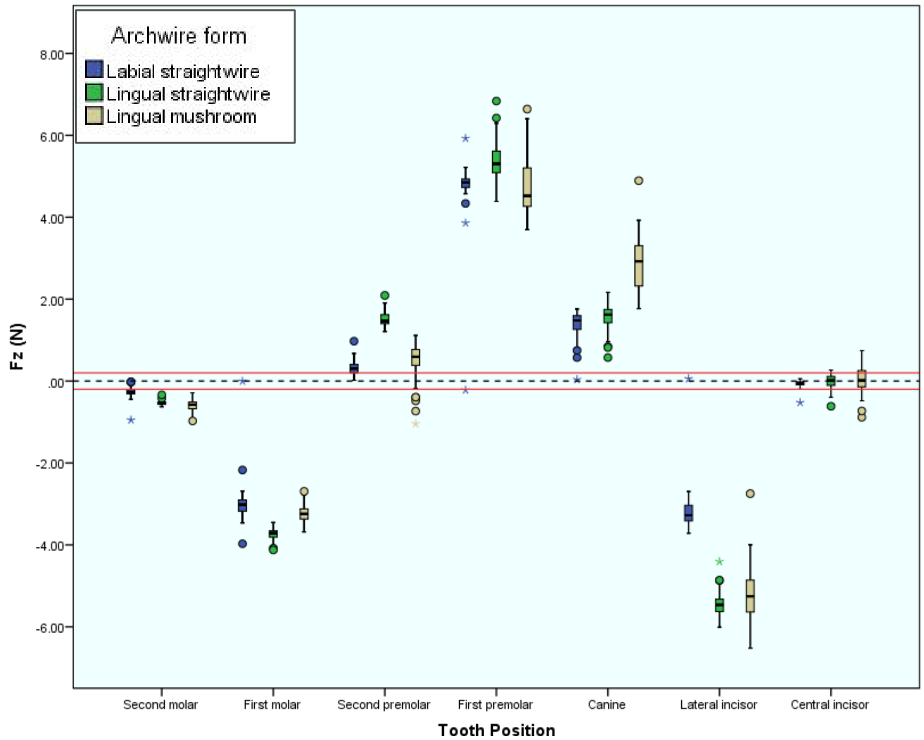

Figure B.1 Boxplot of F_z levels of each tooth position and archwire form. Values between the red horizontal lines are clinically insignificant ($|F_z| < 0.2N$).

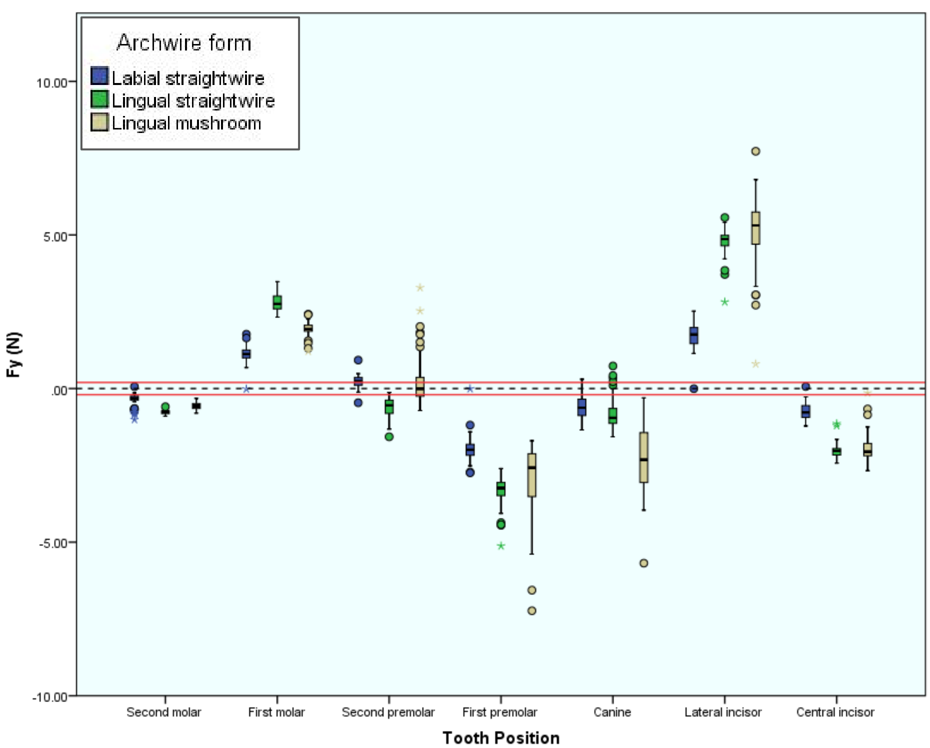

Figure B.2 Boxplot of F_y levels of each tooth position and archwire form. Values between the red horizontal lines are clinically insignificant ($|F_y| < 0.2N$).

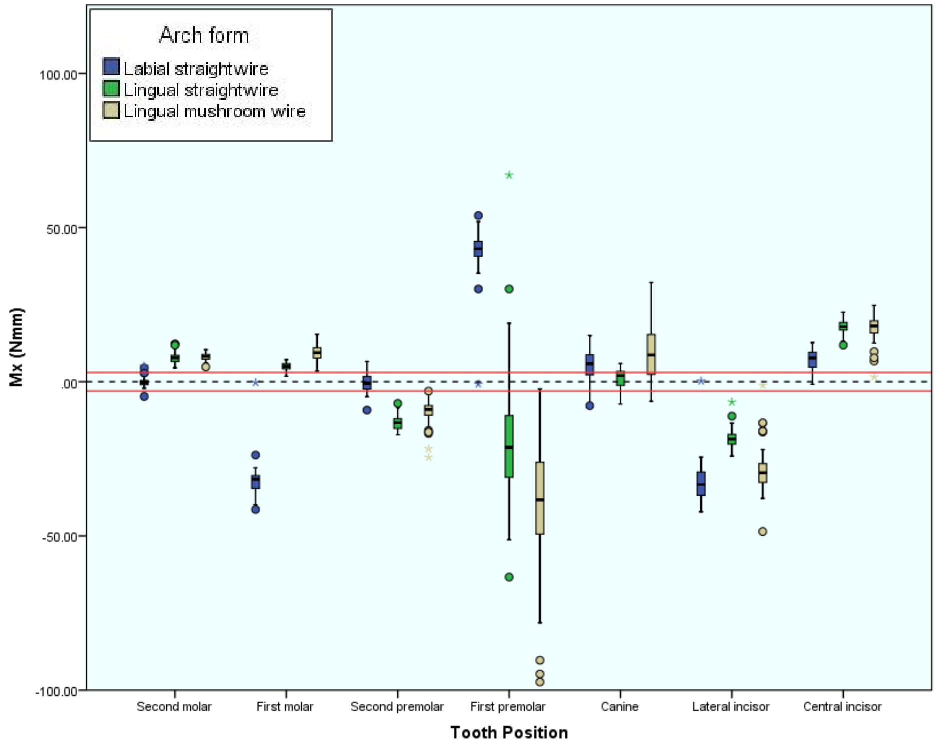

Figure B.3 Boxplot of M_x levels of each tooth position and archwire form. Values between the red horizontal lines are clinically insignificant ($|M_x| < 3$Nmm).

Table B.1 Two-way mixed MANOVA test results with Pillai's Trace Statistic

Effect	Value	F	Hypothesis df	Error df	p-value	Partial η^2
Archwire form	1.29	108.41	6	358	< 0.0005	.645
Tooth	1.00	4525.02	18	163	< 0.0005	.998
Archwire form*Tooth	1.95	341.85	36	328	< 0.0005	.974

Table B.2 Box's Test of Equality of Covariance Matrices

Box's M	F	df1	df2	p-value
5039.21	8.61	462	51963.11	< 0.00005

Table B.3 Mauchly's Test of Sphericity

Within Subjects Effect	Measure	Mauchly's W	Approx. Chi-Square	df	P-value	Epsilon (Greenhouse-Geisser)
Tooth	Fy	.002	1110.16	20	< 0.0005	.42
	Fz	.02	689.75	20	< 0.0005	.50
	Mx	< 0.0005	1391.03	20	< 0.0005	.27

Table B.4 Tests of Within Subjects Effects with Greenhouse-Geisser Correction

Source	**Measure**	**ε^***	**df**	**Mean Square**	**F**	**P-value**	**Partial η^2**
Tooth* Archwire form	F_z	10.69	2	5.35	130.64	< 0.0005	0.59
	F_y	0.73	2	0.36	19.77	< 0.0005	0.18
	Mx	3281.64	2	1640.82	648.73	< 0.0005	0.88
Error (Tooth)	F_z	3.31	180	0.02			
	F_y	111.32	334.59	0.33			
	M_x	455.267	180	2.53			

*Epsilon = sum of squares