Digital assessment of three-dimensional tooth movement during orthodontic activation using an *optimised typodont system*

**Austin Kang**  
BDS (Otago), MHealSci, PGDipSci, BSci.

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“If you can dream it, you can do it”
- Walt Disney

“Whether you think you can or think you can’t, either way you are right”
- Henry Ford

“Really, the only thing that makes sense is to strive for greater collective enlightenment”
- Elon Musk

“Success is a lousy teacher. It seduces smart people into thinking they can’t lose”
- Bill Gates
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Hwik.
Thesis Outline

For convenience of future publications, this work is divided into five chapters as a hybrid-Thesis. Some degree of overlap was inevitable due to the nature of such formatting, in which case repetition was minimised by referring to relevant chapters within the thesis. This work is organised as follows:

Chapter 1 – Review of the Literature

A general introduction is provided on orthodontic tooth movement, with review of the literature on the principles of biomechanics, current tools available in studying biomechanics, three-dimensional tooth movement, and rationale for testing the selected activations used in this study.

Chapter 2 – Core Materials and Methods

This chapter covers the methodological details, including the study design, data collection, and associated analyses. More detailed description of methods to investigate the study’s specific objectives are covered in Chapters 3 and 4.

Chapter 3 – Development of the Optimised Typodont System

The experiments described in this chapter highlight the development of the digital tool for assessing three-dimensional tooth movement produced on a wax-typodont. The tool was then used to test an archwire activation with a reversed curve of Spee, and the results compared with the relevant literature.
Chapter 4 – First Order Activations

The Chapter reviews archform considerations that are necessary during orthodontic treatment. Common first order archform reshaping activations were tested using the optimised typodont system, and their indications and precautions discussed based on the results.

Chapter 5 – General Discussion and Conclusion

A general discussion of the study’s findings are included in this chapter. In particular, the limitations of the study are highlighted, along with directions for further research.

Chapter 6 – Appendices
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List of Abbreviations

2D  2-Dimensional
3D  3-Dimensional
CAD/CAM  Computer Aided Design / Computer Aided Manufacture
CoR  Centre of Resistance
DoF  Degrees of Freedom
FEM  Finite Element Modelling
FHA  Finite Helical Axis
OMSS  Orthodontic Measurement and Simulation System
PDL  Periodontal Ligament
PLA  Polylactide
RMS  Root Mean Square
STL  Stereolithography
Chapter 1 – Review of the Literature

Understanding Orthodontic-related Tooth Movement

Methods to Simulate Orthodontic Tooth Movement

Tooth Movement Assessment

Rationale for the Activations Selected in this Study

Study Objectives

References
1.1 Understanding Orthodontic-related Tooth Movement

1.1.1 Introduction

The primary objective of orthodontic treatment is to achieve an optimal aesthetic and functional occlusion (Andrews, 1972; Bowman, 2001; Sharma and Sharma, 2012). This requires careful consideration of individual tooth position involving comprehensive clinical, radiographic and model analyses (Arnett and Gunson, 2004; Brown, 1981; Kirschen et al., 2000a; Kirschen et al., 2000b). Once the optimum final tooth position has been determined, the next step would be to move each tooth to the intended desired position within the dental arch.

Accurate control of tooth movement is important to avoid prolonged treatment that can lead to undesirable side effects such as root resorption (Weltman et al., 2010) and enamel demineralization (Pender, 1986). In extreme cases, poor biomechanical control of teeth can result in them being moved outside of the alveolar bone envelope (Evangelista et al., 2010). To minimise iatrogenic effects, a thorough understanding of the principles behind tooth movement is crucial. By applying these principles in clinical practice, the movement of teeth may be achieved with more predictability and efficiency.
1.1.2 Principles of Biomechanics

A tooth will move upon the application of force(s) to the crown (Lindauer, 2001). A force is characterised by a point of application, a magnitude, a line of action, and a sense (Lindauer, 2001; Smith and Burstone, 1984).

Depending on the characteristics of the force, the resulting movement can be described as pure translation, a combination of translation and rotation, or pure rotation (Lindauer, 2001; Smith and Burstone, 1984).

A force can produce either of these movements, depending on its line of action relative to the “balancing point” of a tooth (i.e., Centre of Resistance - CoR) (Smith and Burstone, 1984). The location of the CoR, in turn, is dependent on the root configuration, and the periodontal support (Kuhlberg and Nanda, 2005). Pure translation occurs when the line of action of a force passes through the CoR of a tooth (Smith and Burstone, 1984). A combination of translation and rotation occurs when the line of action does not pass through the CoR (Burstone and Pryputniewicz, 1980). Pure rotation requires the application of a force couple, which is defined as two forces of equal magnitude, different yet parallel lines of action, and in opposite sense (Lindauer, 2001).

Typically, orthodontic tooth movement occurs as the result of a complex combination of forces, each producing a tendency to translate and/or rotate the tooth. All the translational and rotational effects are combined to produce a single net roto-translational movement (Smith and Burstone, 1984).

Based on these biomechanical principles, the resultant tooth movement can theoretically be solved by identifying all the force(s) acting on a tooth.
1.1.3 Quantification of Orthodontic Forces

During conventional orthodontic treatment, forces can be applied using various activations of the archwire (Figure 1.1). The force systems resulting from these activations are difficult to determine for several reasons. First, the forces are *statically indeterminate* and cannot be quantified using the laws of statics alone (Burstone and Koenig, 1974; Lindauer, 2001). Second, the force systems are *dynamic* since the magnitude and the direction of the forces change continuously over the period of the orthodontic activation. Third, the forces are *three-dimensional*, with a component in all three planes of space (Drescher *et al.*., 1991).

Although a number of measuring devices have been developed in an attempt to quantify such complex forces (Friedrich *et al.*., 1999; Fuck and Drescher, 2006; Kuo *et al.*, 2001; Lapatki and Paul, 2007; Menghi *et al.*, 1999), their routine use is either impractical, or lacks the accuracy needed for reliable force quantification.

---

**Figure 1.1.** Archwire activation of reversed curve of Spee. A, an archwire with reversed curve of Spee. B, wire engaged to teeth. C, resultant tooth movements.
1.1.4 The Need for Tooth Movement Simulation

One approach to studying the effects of orthodontic arch wire activation is to measure individual tooth position before and after activation. With this approach, the effects of an activation can be described without quantifying the exerted forces (Burstone et al., 1978; Drescher et al., 1991). Any change in tooth position occurring during an activation can be obtained by simulating the process in a controlled experimental environment.

The most ideal setup would be an in-vivo experiment (Lapatki and Paul, 2007), which is not always feasible due to practical and ethical reasons. An in-vivo experiment requires standardisation of a passive baseline occlusion, which is impractical to establish on all the study participants. Moreover, this experiment would require standardisation of the activation of interest, which would cause undesirable dental movement for many participants. This poses ethical challenges with the possible complications associated with the resulting malocclusion, and correction needed upon completion of the study. While animal models have been used, the studies were mostly limited to simple activations without the use of brackets (Andrade et al., 2007; Braga et al., 2011; Danz et al., 2013; Dibart et al., 2014; Han et al., 2014; Wu et al., 2010; Young et al., 2013). Some studies have used aligners (Sombuntham et al., 2009) or tailor-made bands to simulate clinical situations (Al-Awadhi et al., 2015; Kraus et al., 2014). Nevertheless, clinical relevance of the results are questionable, with differences in tooth and root morphology, as well as possible biological responses being some of the variables not taken into account.

Due to the difficulties in performing an in-vivo investigation, in-vitro experiments have become pivotal in this area of research. Since tooth movement is the product of both a
mechanical stimuli (i.e. activation) and a biological response of the surrounding tissues (Smith and Burstone, 1984), the main limitation of in-vitro studies is the inaccuracies involved in mimicking the mechanobiological responses which occur during this process (Clifford et al., 1999). Fortunately, the mechanical properties of an activation remain identical to the clinical situation. Moreover, the observed tooth movements of in-vitro studies are reported to be similar to clinical reports, and continuous advances in this area have been reducing such disparities further (Bourauel et al., 2000; Clifford et al., 1999), making them an acceptable tool in studying orthodontic biomechanics. To date, various in-vitro simulation systems have been developed and used in published studies, each with their own advantages and disadvantages.
1.2 Methods to Simulate Orthodontic Tooth Movement

1.2.1 Finite Element Modelling

Computer-based simulations are gaining popularity and are utilised extensively in literature reports. Finite Element Modelling (FEM) involves digital construction of the dento-alveolar complex, using an arbitrary number of elements (or building blocks). Each of the elements in the complex represents a specific anatomical structure, such as enamel, dentine, periodontal ligament (PDL) or alveolar bone. The distinction is made by assigning different properties (e.g. Young’s modulus and Poisson’s ratio) to the elements, allowing behaviour of the structures to mimic those in-vivo. Using FEM models, orthodontic activations can be applied to simulate movement with minimal time and cost, and also replicate biological responses in theory.

Despite the sophisticated computation involved in FEM, inaccuracies in mimicking the biological response persist. One reason for such errors is the complex biological properties not being reproducible in FEM, which necessitate numerous assumptions (Papadopoulou et al., 2013; Toms et al., 2002). The uniform thickness of the PDL space is a common example (Ammar et al., 2011; Bourauel et al., 1999; Field et al., 2009; Geiger and Lapatki, 2014), where its intra- and inter-dental variability (Hirashima et al., 2016; Toms et al., 2002) is not reproduced. Uniform PDL properties, despite the dynamic orientation across the PDL space (Hirashima et al., 2016) is also frequently assumed (Field et al., 2009; Geiger and Lapatki, 2014).
Moreover, accuracy of the assigned properties of the anatomical structures is crucial in simulating representative clinical movements (Bourauel et al., 1999). Such properties, however, are complex, with the exact values yet to be elucidated. In particular, the Young’s modulus of PDL has been found to be non-linear where the value changes at different magnitude of the force, and anisotropic where the value is dependent on the direction of the force (Papadopoulou et al., 2013; Toms et al., 2002).

Although these biological limitations are similar to those found in other in-vitro systems, the clinical relevance of the simulated activations may also be challenged, as manual application of orthodontic activation is not possible via FEM. Digital application of a constant force in a known direction does not represent an orthodontic activation used in a clinical setting (Cifter and Sarac, 2011; Kojima et al., 2012; Sung et al., 2010; Tominaga et al., 2014).

1.2.2 Three-dimensional Force Sensor

One of the earliest simulation systems developed is the Orthodontic Measurement and Simulation System (OMSS), which utilises two independent three-dimensional force sensors (Drescher et al., 1991). Each of the sensors mimics a tooth to which orthodontic activations can be engaged. The sensors are also capable of moving in the direction of the measured force, thereby facilitating movement simulations (Bourauel et al., 1992).

The main drawback of the system is the number of sensors, as activations involving more than two teeth cannot be simulated. This strictly limits the range of activations that can be tested since most orthodontic activations are engaged to multiple teeth. Furthermore,
movement simulations are based on mathematical calculations using a fixed location of the CoR (Pedersen et al., 1990). The position of CoR is known to be inconsistent throughout tooth movement (Kuhlberg and Nanda, 2005), and its location is also suggested to exist as a three-dimensional axis (Viecilli et al., 2013). Therefore, the simulated movements based on such mathematical calculations would be an oversimplification.

1.2.3 Wax-typodont

A typical orthodontic typodont is composed of artificial teeth embedded in a wax base. Orthodontic activations are typically applied to the teeth by attaching brackets and wires, and movement simulated with the softening of the wax base by evenly elevating the temperature.

A typodont is the only system currently capable of simulating movement with a full range of clinically relevant orthodontic activations. Simulation of an orthodontic activation involving the entire arch also allows the movement of each individual tooth to be assessed. As a robust tool which is simple to operate, it is widely used both in teaching institutions to study biomechanical principles, as well as in research (Lee et al., 2014; Li, 2014; Ogura et al., 1996; Romeo et al., 2010; Sangcharearn and Ho, 2007a; 2007b).

Traditional typodonts are still problematic due to difficulties achieving a consistent temperature across the full thickness of the wax, thereby leading to differential rates of tooth movement at different depths of the wax arch. Where a water-bath or an oven is used to soften the wax base, conduction of heat commences at the superficial surface and gradually
proceeds to the core. Consequently, the rate of movement of a tooth would be expected to
vary depending on its position in the wax, thereby producing errors in the simulation. A
number of modifications have been attempted to ensure a uniform rate of tooth movement
within the base. The Calorific Machine System involved applying heat directly to the teeth,
causing the wax to soften evenly around the individual tooth roots (Rhee et al., 2001). Others
have used gelatine as the base material, which undergoes time-dependent deformation under
mechanical loading (Clifford et al., 1999). Despite these attempts at standardising the rate
of tooth movement within the wax base, there is currently no available data on the validity
of these techniques in representing orthodontic tooth movement.

Wax typodonts are generally used for a visual analysis of the effect of archwire activation
on tooth position (Clifford et al., 1999). Since these movements occur in three-dimensions,
their accurate quantification is often difficult to determine.
1.3 Tooth Movement Assessment

1.3.1 Assessing Tooth Movement in 3-dimensions

Orthodontic tooth movement occurs in three dimensions, which are the anterior-posterior, vertical, and transverse. Since tooth movement is often multi-planar, an objective assessment method must include information in all three planes.

Classically, tooth movement assessments were two-dimensional (Isaacson et al., 1993; Pedersen et al., 1990; Smith and Burstone, 1984), in either the sagittal, occlusal or frontal planes. However, each of the planes can only assess movements in two of three directions. In the sagittal plane, the movements in the anterior-posterior and the vertical directions can be assessed. In the occlusal plane, the two directions are anterior-posterior and transverse. In the frontal, they are transverse and vertical. Therefore, assessing tooth movement in a particular plane does not permit assessment in one of the three planes, giving an incomplete picture of the change in tooth position.

For example, molar intrusion is typically accompanied by uncontrolled tipping (Cifter and Sarac, 2011), where the crown and the roots are displaced in the transverse direction. Therefore, the movement should not be assessed in the sagittal plane, which is incapable of assessing such transverse movements. Occlusal plane assessments, on the other hand, cannot evaluate vertical movements. In the coronal plane, anterior-posterior movements such as incisor proclination cannot be accurately assessed.

This highlights the need for a comprehensive three-dimensional assessment of tooth movement in all three directions.
In reality, tooth movement changes direction continuously and should be described using an instantaneous center of rotation in two dimensions, or a helical axis in three dimensions (Gallo et al., 2000). A detailed description of the properties of a helical axis and its relationship to orthodontic tooth movement is beyond the scope of this review.

1.3.2 Six Degrees of Freedom

To assess the movement of teeth in three-dimensions, six different types of movement, or six degrees of freedom (DoF), need to be considered (Rubin et al., 1983). These are generally referred to as mesio-distal, intrusive-extrusive, bucco/labio (lingual/palatal), tipping, torqueing, and rotational movements (Figure 1.2).

Previous studies have attempted to assess tooth movement using a single landmark (Burstone and Pryputniewicz, 1980; Burstone et al., 1978). By describing changes to the landmark position (Figure 1.3A), the movements were assessed using 3DoF. Using these methods, tooth movement could be assessed in terms of only three translational movements (mesio-distal, intrusive-extrusive, and bucco/labio-lingual/palatal). The situation improved by using two landmarks (Figure 1.3B), which could assess two additional rotational movements (i.e. 5DoF) (Yoshida et al., 2000; Yoshida et al., 2001). However, a comprehensive assessment with 6DoF could only be achieved with at least three
landmarks (Figure 1.3C) (Ashmore et al., 2002; Hayashi et al., 2002; Hayashi et al., 2006; Jeon et al., 2009).
Figure 1.3. Number of landmarks. A, one landmark illustrating movement with three degrees of freedom. B, two landmarks describing movement with five degrees of freedom. C, three landmarks describing movement with six degrees of freedom.
In addition to the number of landmarks, their location also seems to play a crucial role in the assessment of tooth movement. Indeed, a particular movement can be assessed in a completely different way with differing landmark locations (Paul, 1981). This can be illustrated in an example of uncontrolled mesial tipping of a molar. Ideally, the movement in this example should be analysed as a pure counter-clockwise rotation in the sagittal plane (Figure 1.4A). However, with the landmarks located on the surfaces of the crown, the movement would be analysed as a counter-clockwise rotation, as well as a mesio-intrusive translation (Figure 1.4B). On the other hand, landmarks on the root surfaces would analyse the movements with a disto-extrusive translation (Figure 1.4C). Therefore, careful consideration must be given to both the number and the position of the landmarks for a meaningful assessment of the observed movements.

![Figure 1.4](image.png)

**Figure 1.4.** Importance of the tooth landmark locations. **A.** Pure-counter-clockwise rotation of a molar. **B.** Landmarks on the coronal surfaces, showing the movement as a counter-clockwise rotation, as well as a mesio-intrusive translation. **C.** Landmarks on the root surfaces, showing the movement as a counter-clockwise rotation, as well as a disto-extrusive translation.

In summary, tooth movement occurs simultaneously in the anterior-posterior, vertical, and transverse directions. Both translations and rotations can occur along each of the three directions, giving rise to movements in six DoF. Only three-dimensional assessments using
at least three different landmarks on or within a tooth are capable of assessing movement in all six DoF. It is also important to give careful consideration to the landmark locations, which can cause the same movement to be analysed in different ways. Classically, tooth movement has been assessed using CoR as the reference (Lindauer, 2001), where both the translational and the rotation movement of the CoR have been used to represent the movement of the whole tooth (e.g. rotation around the CoR is considered to be pure rotation). Therefore, assessment of tooth movement centred around the CoR would seem to be the most clinically relevant.
1.4 Rationale for the Archwire Activations Selected in this Study

1.4.1 Reversing the Curve of Spee

Deep bites are a common condition affecting both adults and children, characterised by an increased overlap between the upper and lower incisor teeth (Strang, 1950). It is known to have potentially detrimental effects on periodontal health (Gould and Picton, 1966), temporomandibular joints (Alexander et al., 1984; Thompson, 1972), and aesthetics (Janzen, 1977), and its correction is often a major component of orthodontic treatment.

Correction of a deep bite involves either the intrusion of incisors, extrusion of molars or a combination of both (Weiland et al., 1996). The decision depends on multiple patient factors, such as the skeletal and soft tissue relationships, and the remaining growth potential (Upadhyay and Nanda, 2015). In cases with an increased vertical dimension, intrusion of incisors is absolutely indicated. Common methods used in clinical practice to intrude the incisors are the segmented or bioprogressive intrusion arches, or a continuous arch wire with a reverse curve of Spee (Sifakakis et al., 2010).

Unlike the effects of an intrusion arch, tooth movement associated with a continuous archwire incorporating a reverse curve of Spee are poorly understood. The forces exerted by such continuous archwires are statically indeterminate and are impossible to predict. In fact, the unpredictable nature of the forces generated during such an activation have been suggested as a contraindication to its use (Sifakakis et al., 2010).
A number of studies have focussed on investigating the effects of a continuous archwire with a reverse curve of Spee (Clifford et al., 1999; Sifakakis et al., 2010; Weiland et al., 1996). There is general consensus in the literature that a slight intrusion of the incisors, as well as extrusion of the posterior teeth occurs. However, there are no reports supporting the widely held view of flaring of the incisors (Braun et al., 1996; Woods, 1986). Furthermore, while premolars and canines are also affected by this activation, this effect was investigated in only one study in which the full three-dimensional movement was not analysed (Clifford et al., 1999).

Although arch wires with a reverse curve of Spee are widely used to correct deep bites, the resultant three-dimensional movement of individual teeth remains unknown.

1.4.2 Archform Reshaping

A single universal archform for orthodontic treatment had been a topic of much debate throughout the history of orthodontics (Jain and Dhakar, 2013). Although many archforms have been described, including a Parabolic, Bonwill-Hawley, Brader, Conic Section, Catenary, Pentamorphic, and ‘Standardised’ (Brader, 1972; Hawley, 1905; McLaughlin et al., 2002; Proffit et al., 2007; Rickets, 1979; Sampson, 1981), none have been found to be an adequate representation of those in the general population (Magness, 2000; White, 1978). Importantly, these suggested archforms result in treatment-induced reshaping of the original archform, which is found to have a high tendency of relapse (de la Cruz et al., 1995). Therefore, the use of a one-size-fits-all archform is now generally discouraged, where
maintenance of the original archform throughout treatment is widely accepted (Felton et al., 1987).

Nonetheless, reshaping of the archform is often necessary to coordinate maxillary and mandibular archforms (Lee, 1999; McLaughlin et al., 2002), or else transversal malocclusions manifest in the form of crossbites or scissors-bites (Thilander et al., 1984). The underlying cause of the archform discrepancy dictates the treatment modality. Skeletal causes are often treated using various orthopaedic appliances with or without surgical assistance. However, dentoalveolar causes such as asymmetric mechanics (e.g. unilateral intermaxillary elastics) or extractions often involve conventional orthodontic treatment with reshaping of an archwire (McNally et al., 2005; Oh et al., 2011).

An archwire may be reshaped via selective expansion or constriction, depending on the presenting malocclusion and desired tooth movement. However, there is a general lack of understanding as to the effects of any such adjustments. While the transverse effects of wire expansion at the molars are well documented (Kraus et al., 2014; McNally et al., 2005), little is known about the effects at the premolars and incisors, which are also affected by an expanded archwire. Other widely used archforms, such as those due to constricted or asymmetrical activations, have also not been investigated to the best of our knowledge and the accompanying movements are still poorly understood.

Archwire reshaping activations are statically indeterminate and their effects can be difficult to predict (Lindauer, 2001). With experimental tooth simulations, the likely movements can be better understood thus improving the predictability and efficiency of their use.
1.5 Study Objectives

The aim of the project is to develop and test a tool (*i.e.* optimised typodont system) for analysing 3D tooth movements that occur during a number of first and second order orthodontic activations: (1) reversing the curve of Spee; (2) expanding at the molar region; (3) squaring the arch wire to widen across the premolars; (4) tapering the arch wire to narrow across the canines; (5) use of an asymmetrical archwire with the vertex located on the lower right canine.
1.6 References


Chapter 2 - Core Materials and Methods

Overview of the Study Design

Optimisation of the Wax-typodont

Baseline (T₀) Set-up

Digitisation of T₀

Testing Orthodontic Activations (T₁)

Digitisation of T₁

T₀ and T₁ Registration

Assessment of Tooth Movement

Data Analysis

Māori Consultation and Ethics

Funding

References
2.1 Overview of the Study Design

This study involved optimisation of the conventional orthodontic wax-typodont to allow 3D information of the typodont to be easily transferred into the digital environment. This optimised typodont was then used to test a number of orthodontic activations (i.e. reversing the curve of Spee, expanding across the molars, squaring, tapering, and asymmetrical adjustment of the arch form). The typodont setup was digitised before (T₀) and after (T₁) the specific activation. Once digitised, a digital methodology was developed to allow simulated tooth movements to be assessed in three-dimensions (3D) with six Degrees of Freedom (6DoF).

This resulted in a novel tool to study different orthodontic activations (i.e. optimised typodont system) by combining the optimised wax-typodont with the digital method of assessing tooth movement.
2.2 Optimisation of the Wax-typodont

The optimised wax typodont setup comprised three parts: a) artificial teeth with attached brackets; b) a wax-arch that held the teeth; and c) a rigid base.

*Teeth with attached brackets*

A set of fourteen sequential teeth from the lower left second molar to the lower right second molar were included in the optimised typodont. The teeth were fabricated from digital tooth models (TurboSquid, New Orleans, USA, Figure 2.1A). The digital models were 3D-printed (Figure 2.1B) using Polylactide (PLA) at a 100 µm layer resolution (Replicator 2; Makerbot, New York, USA).

Pre-adjusted McLaughlin-Bennet-Trevisi prescription edgewise brackets with 0.022-inch slots (Avex; Opal Orthodontics, Utah, USA) were bonded manually to the teeth along the vertical long axis of the crown at the estimated center of the clinical crown, using an instant-adhesive (Loctite 406; Henkel, Arizona, USA).

*Wax-arch*

The wax-arch was used to hold the teeth in the desired position. Digital software was used
to design the wax-arch as a 3D envelope of uniform thickness (3mm) around the tooth roots (3D Studio Max, release 13.0; Autodesk, California, USA, Figure 2.2). This was to facilitate consistent glass-transition of wax (i.e. softening) during heating across all the typodont teeth.

Previous typodont studies have used different types of wax for fabrication of the wax-arch. However, no specific material had been recognized as the gold standard for typodont experiments.

Therefore, a pilot study was carried out to test the glass-transition properties of different waxes. The tested waxes included pink wax (Base plate wax - Regular; Kerr Corporation, California, USA) and sticky wax (Sticky wax; Kerr Corporation, California, USA). The ideal properties of the material included adequate flow near the intra-oral temperature range (i.e. allowing tooth movements around 35 - 36 °C; < 58.5°C) (Moore et al., 1999), and structural integrity during tooth movement.

During heating of pink wax in a water bath, tooth movement occurred at 38 ± 1°C. However, the teeth detached from the wax during extrusive movements due to poor adhesion. Using sticky wax, tooth movement were observed at 44 ± 1°C, and good structural integrity of the wax was maintained during the full range of 3D movement. Based on these results, sticky wax was chosen as the suitable embedding material for the wax-arch and the typodont
experiments.

**Rigid base**

A rigid base was used to support the wax-arch (Splitex Counter Plates; Amann Girrbach, Koblach, Austria), and to act as a fiducial marker for the registration (*i.e.* 3D superimposition) of the digitised typodont models.

**Master Stent**

A master stent was used throughout the study to assemble all the components of the wax-typodont into a well-aligned occlusion. The master stent was modelled via computer-aided-design and computer-aided-manufacture (CAD/CAM) methodology.

Specific software (3D Studio Max, release 13.0; Autodesk, California, USA) was used to set up the digital tooth models in a well-aligned dental arch. A 3-mm shell surrounding the roots of each tooth was designed (Figure 2.2A), combined with the teeth as a single unit and 3D printed using PLA. Orthodontic Tray Wax (Kerr Corporation, California, USA) was attached on the crown of each tooth to remove undercuts and minimize interference of the master stent with brackets. The rigid base was then attached below the wax-arch design (Figure 2.2B), and the master stent was constructed for use throughout the entire study as baseline settings (Figure 2.3).
### 2.3 Baseline (T₀) Set-up

The baseline typodont was constructed using the master stent described earlier. The 3D-printed teeth with attached brackets and the rigid base were positioned into the master stent (Figure 2.4A). The wax was heated at 70 °C until a homogeneous melting was obtained, and poured into the master stent and left at room temperature until it solidified (Figure 2.4B). The stent was then removed to recover the wax-typodont setup (Figure 2.5).

A 0.019 x 0.025-inch stainless steel archwire (Permachrome - Ovoid; 3M, Minnesota, USA) was engaged into the bracket slots with elastomeric modules (Mini-Stik™; 3M, Minnesota, USA). The typodont was heated in a water bath (Whip Mix, Kentucky, USA) at 44 ± 1 °C until the wire appeared passive, and then cooled in a water bath (5°C) for five minutes.

![Figure 2.4](image)

**Figure 2.4.** Construction of the baseline typodont. A, teeth with brackets embedded into the master stent, supported by a removable plastic base. B, rigid base embedded, and liquid wax poured into the master stent.

The required temperature of 44 ± 1°C for tooth movement within the wax-arch had been identified during a pilot study as described earlier.

To confirm the passivity of the wire, the typodont was heated for an additional 15 minutes.
A standardised photograph was taken of the baseline typodont before and after the additional heating process (EOS 700D; Canon, Tokyo, Japan, ISO 200, shutter speed 1/250, aperture F22), and were visually compared. This process was repeated until no further movement was evident.

2.4 Digitisation of $T_0$

The crowns of the typodont teeth at baseline were digitised using a 3D surface scanner (Ceramill Map400; Amann Girrbach, Koblach, Austria), and saved in stereolithography (STL) file format (Figure 2.6).

2.5 Testing Orthodontic Activations ($T_1$)

Each of the orthodontic activations was tested on a reconstructed baseline typodont until the activated wire became passive. Please refer to Chapter 3 and Chapter 4 for specific details about the different activations that were analysed.

A pilot study was conducted to identify the duration required for each of the activation wires
to become fully passive at a water bath temperature of 44 ± 1°C. This involved engaging each of the activation wires into a newly prepared baseline typodont and heating in the water bath (44 ± 1°C) at 15-minute intervals. Standardised photographs were taken before and after each interval which were visually compared to confirm the passivity of the wire. This process was repeated until no further movement was evident.

All the tested activations were confirmed passive when heated for a total of 75 minutes. No notable movement were evident when the passive wire was tested for a period of 120 minutes. From these results, the optimal heating time for all experiments was set at 90 minutes, which would allow sufficient time for all activations to be fully expressed.

2.6 Digitisation of T₁

The resultant typodonts were digitised after each activation (T₁) and was stored in an STL file format. Each activation was repeated three times.
2.7 T₀ and T₁ Registration

The typodont setups obtained before and after each activation (T₀, T₁) were registered using the rigid base as the fiducial marker and imported in a common set of 3D coordinate system (Figure 2.7). This registration was performed by default during the 3D-scanning procedure (Ceramill Map400; Amann Girrbach, Koblach, Austria).

2.8 Assessment of individual Tooth Movement

*Defining individual tooth positions at T₀ in the Cartesian coordinate system*

The baseline typodont (T₀) was superimposed with individual 3D tooth models to replicate the setup inclusive of the dental roots, in a digital space.

To achieve an accurate setup, each 3D tooth model was superimposed individually to the corresponding typodont crown (Figure 2.8) via a distance-based matching algorithm (Meshlab v1.3.4Beta; Visual Computing Lab – ISTI – CNR, Pisa, Italy).

The individual 3D tooth models used for superimpositions were created by digitising the
typodont teeth back into the digital space, instead of using the original 3D tooth models. This improved the accuracy of superimpositions, as the corresponding surfaces were almost identical.

Each tooth element at T₀ was then described in an individual Cartesian coordinate system, with the origin (0,0,0) set at the Center of Resistance (CoR), and the axes orientated according to the slot of the corresponding bracket (Figure 2.9). The x-axis was parallel to the mesio-distal, y-axis parallel to bucco-lingual, and z-axis parallel to intrusive-extrusive directions of the bracket slots.

**Estimating the Center of Resistance (CoR)**

The CoR of each tooth was estimated at approximately two-thirds of the root length for incisors, canines, and premolars, and at the level of the furcation for molars along the long axis of each tooth (Burstone and Pryputniewicz, 1980; Dermaut *et al.*, 1986).

The long axis was determined by tracing a line connecting the geometrical centroid of the whole tooth and the root-centroid. The geometrical centroid for each tooth was calculated as the average position of the whole surface mesh of the tooth, whereas the root-centroid was calculated as the average position of the surface mesh of the root only. Centroids were calculated using a specific software and a custom-made algorithm (Schroeder *et al.*, 2006).

**Axes Parallel to the Bracket Slots**

The digital models of the brackets used for the optimised typodont setup were obtained from the manufacturer. The models by default were orientated in the 3D coordinate system with the axes parallel to the mesio-distal, bucco-lingual, and intrusive-extrusive directions of the
bracket slot. Three axes that are parallel to each of the three directions were created at the base of the bracket slots (3D Studio Max, release 13.0; Autodesk, California, USA, Figure 2.10A). The three axes were then translated in the 3D space so the origin of the axes was coincident with the position of CoR (3D Studio Max, release 13.0; Autodesk, California, USA, Figure 2.10B). Arbitrary reference points along the three axes were plotted, (5,0,0), (0,5,0), (0,0,12.5), which were used for tooth movement assessments as described later.

**Defining Tooth Positions at T₁ in the Cartesian Coordinate System**

The individual 3D tooth models at T₀ were combined with their CoR, the three axes parallel to the bracket slots, and the arbitrary reference points along the three axes. The combined unit was duplicated, and superimposed individually with the corresponding typodont crowns after activation (T₁) using the method as described earlier.

Individual tooth models at T₁ were located in the same Cartesian coordinate system as their tooth models at T₀.
**Tooth Movement with 6DoF**

For each tooth, the change in the tooth position from $T_0$ to $T_1$ was assessed and described with 6DoF.

The *mesio-distal*, *bucco-lingual*, and *intrusive-extrusive* movements were assessed as changes in the location of CoR from $T_0$ to $T_1$ in the $x$, $y$, and $z$ axes respectively (Figure 2.11):

- **Mesial-Distal translation**
  \[
  \Delta x \ (mm) = x_1 - x_0
  \]

- **Bucco-Lingual translation**
  \[
  \Delta y \ (mm) = y_1 - y_0
  \]

- **Intrusive-Extrusive translation**
  \[
  \Delta z \ (mm) = z_1 - z_0
  \]

*Figure 2.11.* Tooth movement described as the change in the position of CoR from $T_0$ to $T_1$. A, Mesio-Distal movement in the $x$-axis. B, Bucco-Lingual movement in the $y$-axis. C, Intrusive-Extrusive movement in the $z$-axis.
The torque, tip, and rotation movements were assessed as the rotations from T₀ to T₁ around the mesio-distal, bucco-lingual, and intrusive-extrusive axes, respectively. Arbitrary points along the three axes parallel to the bracket slots were used as the reference points to calculate all three ‘rotational’ movements (Figure 2.12):

\[
\begin{align*}
\text{Torque (roll)} & \quad R_x(\gamma)^\circ = \tan^{-1}\left(\frac{x_1^{IE} - x_1}{z_1^{IE} - z_1}\right) \\
\text{Tip (pitch)} & \quad R_y(\beta)^\circ = \tan^{-1}\left(\frac{y_1^{MD} - y_1}{x_1^{MD} - x_1}\right) \\
\text{Rotation (yaw)} & \quad R_z(\alpha)^\circ = \tan^{-1}\left(\frac{z_1^{BL} - z_1}{y_1^{BL} - y_1}\right)
\end{align*}
\]

Direction of torque was described using tooth root(s) as the reference (e.g. buccal root torque, if the root of the tooth was displaced out towards the buccal, and the crown in towards the lingual).

Direction of tipping was described also using tooth root(s) as the reference (e.g. mesial root tipping, if the root of the tooth was displaced mesially, and the crown was displaced distally).

Direction of rotation was described using the distal surface of the tooth as the reference, and the direction of its displacement either towards (in) or away from (out) the arch (e.g. distal-out rotation, if the distal surface of the tooth was rotated out towards the buccal, and mesial surface in towards the lingual).
Figure 2.12. Tooth movement described as the change in the angulation of from $T_0$ to $T_1$. A, arbitrary point coordinates on $T_1$ within the three axes parallel to the bracket slot. B, origin of the three axes at $T_1$ (i.e. CoR of $T_0$) reorientated to coincide with CoR of $T_0$. C, torque movement assessed as the rotation around the $x$ (mesio-distal)-axis. D, tipping movement assessed as the rotation around the $y$ (bucco-lingual)-axis. E, rotational movement assessed as the rotation around the $z$ (intrusive-extrusive)-axis.
2.9 Data Analysis:

Data were analysed using conventional descriptive statistics. Mean and standard deviation for movement were calculated using Excel spreadsheet (Office 365 ProPlus; Microsoft, Washington, USA). Errors in superimpositions were estimated using the Hausdorff Distances and surface Root Mean Square (Cignoni et al., 1998). No inference tests were carried out due to the descriptive nature of the study.

2.10 Māori Consultation and Ethical Agreement

Consultation with the Ngāi Tahu Research Consultation committee (Te Komiti Rakahau ki Kāi Tahu) was conducted on June 2016. The committee acknowledged that the research is laboratory-based, and that further consultation is not required.

No ethical approval was necessary as the study did not involve animal or human participants.

2.11 Funding

The study was supported by a Fuller Scholarship, which was awarded on January 2016.
2.12 References


Chapter 3 – Development of the Optimised Typodont

System

Abstract

Introduction

Materials and Methods

Results

Discussion

Conclusions

References
3.1 Abstract

Background: During conventional orthodontic treatment, a highly complex force system is applied to the teeth via different archwire activations. A wax typodont is considered the only model capable of simulating a full range of clinically relevant orthodontic activations, and is widely described in the literature and is used as a teaching tool at training institutions. However, a major limitation of this tool is the inability to quantify the resultant tooth movement.

Aims: The aim of this project was to develop a tool (i.e. optimised typodont system) for assessing 3-dimensional effects of an orthodontic activation across the entire dental arch. Using this tool, tooth movement resulting from an archwire with a reversed curve of Spee was tested and analysed.

Methods: CAD/CAM technology was used to develop the optimised typodont system, which was then used to test an archwire with a reversed curve of Spee on the entire mandibular dentition including the second molars. The experiment was repeated three times and the resulting movement to individual teeth were averaged.

Results: The typodont system that was developed could be reliably used to test an archwire activation and to describe individual 3D tooth displacement with six degrees of freedom. Reversing the curve of Spee led to intrusion of incisor and second molar teeth (<1.0mm), extrusion of the premolar and first molar teeth, and caused pronounced first and third order effects on most teeth. With the three-dimensional assessment, the speculative relative-intrusion resulting from the proclination of incisors (~11deg) and distal crown tipping of the
second molars (~20deg) were also observed.

**Conclusion:** The results of the study show the optimised typodont system to be a promising tool in studying orthodontic tooth movement. An archwire with a reversed curve of Spee has 1st, 2nd, and 3rd order implications that should be taken into account when planning tooth movement.
3.2 Introduction

Orthodontic tooth movement can be produced using a variety of orthodontic arch wire activations. Many activations exert highly complex force systems (Bourauel et al., 1992; Burstone and Koenig, 1974), and the resultant tooth movement can be difficult to predict. This may result in a trial-and-error approach to achieving the desired movement, sometimes involving unwanted movement and subsequent correction (*i.e.* round-tripping). Extensive round-tripping movements can prolong treatment time (Bhowmik et al., 2012), which can then lead to further side effects such as root resorption (Weltman et al., 2010) and enamel demineralisation (Pender, 1986). In extreme cases, poor biomechanical control of teeth can result in them being moved outside of the alveolar bone envelope (Evangelista et al., 2010). To minimise these iatrogenic effects, the predictability of tooth movements from activations are crucial.

Predictability of tooth movement may be improved with an in-depth knowledge of biomechanics and the use of tooth movement simulation tools. To date, various simulation systems have been proposed, each with its own advantages and disadvantages. Finite Element Modelling (FEM) involves computer-based simulation of orthodontic movements based on numeric assumptions of biological properties (Bourauel et al., 1999; Papadopoulou et al., 2013; Toms et al., 2002), which are not necessarily valid (Bourauel et al., 2000; Caputo and Standlee, 1987). Another common tool is the Orthodontic Measurement and Simulation System (OMSS), which simulates orthodontic movements using two independent three-dimensional force sensors (Bourauel et al., 1992; Drescher et al., 1991).
The main drawback of the system is the limited number of sensors, as activations involving more than two teeth cannot be simulated.

An orthodontic typodont is a cost-effective tool that is readily available in teaching institutions. Clinical situations can be closely mimicked, as the testing of an activation also requires manual engagement. The possibility of an entire arch simulation also allows the assessment of each individual tooth movement. As a robust tool which is simple to use, it is widely used to study orthodontic biomechanics, both in clinical and research settings. (Lee et al., 2014; Li, 2014; Ogura et al., 1996; Romeo et al., 2010; Sangcharearn and Ho, 2007a; 2007b). However, a major limitation of the conventional wax typodont is the inability to accurately describe and quantify the movements resulting from orthodontic activations. These movements actually occur in 3D and are difficult to evaluate on the basis of a visual analysis (Koo et al., 2017).

A typical example of an activation that causes complex 3D movements is the so-called “reversed curve of Spee”, which is generally used for the correction of deep bites (Sifakakis et al., 2010). A deep bite with or without palatal impingement of lower incisors is a relatively common feature of a malocclusion, especially in Class II patients (Gould and Picton, 1966; Strang, 1950). Correction of a deep bite involves either the intrusion of incisors, extrusion of molars or a combination of both (Weiland et al., 1996). The 3D tooth movements resulting from the application of a continuous archwire with a reversed curve of Spee are difficult to predict, and have been only scarcely investigated in previous studies (Clifford et al., 1999; Mitchell and Stewart, 1973).
The aim of this study was to develop an optimised typodont system to assess dental three-dimensional movement produced by orthodontic arch wire activation. Using this system, tooth movement resulting from an archwire with a reversed curve of Spee were tested and analysed.
3.3 Materials and Methods

Development of the optimised typodont system

A conventional wax-typodont was optimised during a pilot study described in Section 2.2 of Chapter 2. Briefly, the optimised typodont setup comprised three parts: a) a set of individual artificial teeth with orthodontic brackets attached; b) a wax-arch of uniform thickness (3mm) around the roots of the teeth; and c) a rigid base. The three parts were assembled to form a well-aligned dental arch using a master stent. The 3D information of the optimised typodont setup could be easily transferred to the digital environment.

The optimised typodont could then be used to test and digitize the effects of any orthodontic archwire activation. In the digital environment, the effect of the activation could be assessed as changes in the 3D positions of each tooth before and after the activation. For more details, refer to Section 2.4 - 2.8 in Chapter 2.

Experimental procedure

This typodont system (i.e. optimised typodont system) was used to investigate the effect of an archwire with a reversed curve of Spee on the entire mandibular arch, including the second molars. A passive archwire of identical size was used as a control.

Preformed 0.019 x 0.025-inch Nitinol archwires with a reversed curve of Spee (Nitinol – Reverse Curve; 3M, Minnesota, USA) were used as test archwires, whereas 0.019 x 0.025-inch stainless steel archwires without reshaping (Permachrome – Ovoid; 3M, Minnesota, USA) were used as the control. The default archform from the manufacturer were used to
standardise the archwire activations.

The research setup was prepared in the postgraduate research bench space at the University of Otago. The room temperature of the research space during the experiments was $22 \pm 2^\circ C$ and was measured using a digital thermometer attached to the wall (Brannan, Cumbria, England).

A water bath with a variable temperature range between $30 - 80^\circ C$ (Whip Mix, Kentucky, USA) was used for the experiments. The water bath was placed into an insulating box to improve consistency of the water bath temperature (Polybin; Long Plastics, Christchurch, New Zealand). In addition, a digital thermometer (Brannan, Cumbria, England) was used to continuously monitor and adjust the temperature as necessary.

The baseline typodont setup was prepared as described in Section 2.3 and Section 2.4 of Chapter 2. In brief, the master stent was used to construct a well-aligned optimised typodont setup. A $0.019 \times 0.025$-inch stainless steel archwire was engaged to the setup with elastomeric modules (Mini-Stik™; 3M, Minnesota, USA), and heated in the water bath at $44 \pm 1^\circ C$ for 90 minutes. The temperature and time required for an active archwire to become passive were determined during a pilot study described in Section 2.5 of Chapter 2. The typodont was then cooled in a cold water bath ($5^\circ C$) for 5 minutes, digitised using a 3D-scanner (Ceramill Map400; Amann Girrbach, Koblach, Austria), and saved in a stereolithography (STL) file format as the baseline setting ($T_0$).

The archwire of the baseline typodont was then replaced with the test archwire, i.e. preformed $0.019 \times 0.025$-inch Nitinol archwire with a reverse curve of Spee, and engaged
using elastomeric modules. The typodont was again heated in the water bath at 44 ± 1°C for
90 minutes. The typodont was then cooled in a cold (5°C) water bath for 5 minutes, digitised
using the 3D-scanner, and saved in a STL file format (T1 - reverse curve).

The control activation was tested by engaging a 0.019 x 0.025” stainless steel archwire on a
reconstructed baseline typodont using elastomeric modules. The typodont was heated in the
water bath at 44 ± 1°C for 90 minutes, cooled in a cold (5°C) water bath for 5 minutes,
digitised using a 3D-scanner, and saved in a STL file format (T1 - control).

Both the test and control activations were repeated three times, giving a total of six
experiments. For each of the six repeated experiments, a new archwire was tested on a
standardised baseline setup of a reconstructed typodont. Each of the repeats were carried out
at the same time (6:00pm) over different days, in a random order.

Assessment of tooth movement

Details on tooth movement assessment are given in Section 2.7 and 2.8 of Chapter 2. Briefly,
the typodont setups obtained before and after each activation (T0, T1) were registered using
the rigid base as the fiducial marker. The change in the position of each tooth from T0 to T1
was assessed and described in the Cartesian coordinate system with 6DoF. The axes of the
system were orientated so that the x-axis represented mesio-distal, y-axis represented bucco-
lingual, and z-axis represented intrusive-extrusive directions for each tooth.

The mesio-distal, bucco-lingual, and intrusive-extrusive movements were assessed as
changes in the location of the CoR from T0 to T1 in the x-, y-, z- axes, respectively. The
torque, tip, and rotation movements were assessed as the rotations around the mesio-distal,
*bucco-lingual*, and *intrusive-extrusive* axes, respectively.

**Data analysis**

Data were analysed using conventional descriptive statistics. The mean and standard deviation for each movement were calculated using Excel software (Office 365 ProPlus; Microsoft, Washington, USA). Errors in superimpositions were estimated using the Hausdorff Distances and surface Root Mean Square (Cignoni et al., 1998). The corresponding surfaces used for the error calculations were the fiducial base surfaces between T₀ and T₁, and between the crown surfaces of all fourteen 3D tooth models and the entire arch of T₀ and T₁. The results from all typodont activations were firstly analysed individually, and then averaged for the test and the control archwire activations. No inference tests were carried out due to the descriptive nature of the study.
3.4 Results

*Development of the optimised typodont system*

The *optimised typodont system* was successfully developed, allowing orthodontic archwire activations to be tested and 3D information to be transferred to the digital environment.

The mean Hausdorff Distance between the fiducial bases at $T_0$ and $T_1$ was 0.05mm (min 0.00 mm, max 0.40 mm, RMS 0.07 mm; Figure 3.1A). The mean Hausdorff Distance between the corresponding crown surfaces of all fourteen 3D *tooth models* to the three replicates of $T_0$ was 0.05mm (min 0.00 mm, max 2.33 mm, RMS 0.11 mm; Figure 3.1B). The mean Hausdorff Distance between the corresponding crown surfaces of all fourteen 3D *tooth models* to the three replicates of $T_1$ was 0.05mm (min 0.00 mm, max 2.65 mm, RMS 0.13 mm; Figure 3.1C).
Figure 3.1. Examples of superimpositions, with distance colour mapping to the Hausdorff Distance (0mm, blue; >0.3mm, red). A, superimposition of T₀ and T₁ using the rigid base as the fiducial marker. B, superimpositions of individual 3D tooth models with T₀. C, superimpositions of individual 3D tooth models with T₁.
Control Archwire

The control wire produced minimal movement in all directions (Figure 3.2). Translations of all teeth were less than 0.1mm in all three dimensions, while rotation, torque and tip were less than 0.8deg (Table 3.1). There was minimal variation between the three repeats of the activation as represented by the low standard deviations.
Table 3.1 Tooth movement in 6DoF, produced by control activations

<table>
<thead>
<tr>
<th>Tooth</th>
<th>37</th>
<th>36</th>
<th>35</th>
<th>34</th>
<th>33</th>
<th>32</th>
<th>31</th>
<th>41</th>
<th>42</th>
<th>43</th>
<th>44</th>
<th>45</th>
<th>46</th>
<th>47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mes</td>
<td>0.0 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>0.1 ± 0.0</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.2</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.0 ± 0.2</td>
<td>0.0 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Dis</td>
<td>0.1 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
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<td>0.0 ± 0.0</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td>Buc</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.0 ± 0.0</td>
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<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>Lin</td>
<td>0.2 ± 0.3</td>
<td>0.1 ± 0.3</td>
<td>0.0 ± 0.5</td>
<td>0.0 ± 0.3</td>
<td>0.1 ± 0.3</td>
<td>0.0 ± 0.5</td>
<td>0.0 ± 0.3</td>
<td>0.1 ± 0.4</td>
<td>0.2 ± 0.0</td>
<td>0.3 ± 0.2</td>
<td>0.3 ± 0.4</td>
<td>0.3 ± 0.2</td>
<td>0.4 ± 0.3</td>
<td>0.4 ± 0.4</td>
</tr>
<tr>
<td>Int</td>
<td>0.3 ± 0.2</td>
<td>0.2 ± 0.2</td>
<td>0.4 ± 0.3</td>
<td>0.2 ± 0.3</td>
<td>0.1 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>0.0 ± 0.3</td>
<td>0.1 ± 0.2</td>
<td>0.1 ± 0.2</td>
<td>0.1 ± 0.2</td>
<td>0.0 ± 0.2</td>
<td>0.0 ± 0.2</td>
<td>0.0 ± 0.2</td>
<td>0.0 ± 0.2</td>
</tr>
<tr>
<td>Ext</td>
<td>0.1 ± 0.3</td>
<td>0.0 ± 0.2</td>
<td>0.8 ± 0.1</td>
<td>0.2 ± 0.3</td>
<td>0.0 ± 0.4</td>
<td>0.0 ± 0.3</td>
<td>0.2 ± 0.2</td>
<td>0.2 ± 0.5</td>
<td>0.0 ± 0.5</td>
<td>0.0 ± 0.2</td>
<td>0.2 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.0 ± 0.2</td>
<td>0.1 ± 0.1</td>
</tr>
</tbody>
</table>

Data are presented as means and standard deviations.
Direction of movement for each tooth are orientated by the attached bracket, with the estimated Centre of Resistance as the landmark.

DoF: Degrees of Freedom; Mes, mesial; Dis, distal; Buc, buccal; Lin, lingual; Int, intrusion; Ext, extrusion; Din, distal-in; Dout, distal-out; RtLin, root lingual; RtLab, root labial; RtMes, root mesial; RtDis, root distal.

Figure 3.2. Tooth movement produced by control wire. A, average tooth movement for each tooth. B, raw data of tooth movement from all three repeats.
Reverse Curve of Spee Archwire Activation

Individual movement of all teeth investigated with six DoF are presented in Table 3.2. For this activation, the standard deviations were relatively low indicating consistency of the result over the three repetitions.

The archwire with a reverse curve of Spee produced intrusion of the incisor and second molar teeth (<1.0mm), and extrusion of premolar (~1.5mm) and first molar teeth (~1.0mm). Minimal vertical displacement was produced on the canines (Figure 3.3).

Proclination, with net lingual root torque effect was produced on the incisors and canines. This was greatest for the central incisors (~11.0deg), followed by lateral incisors (~8.0deg), then canines (~1.5deg). Distal root tipping was also produced on incisors and canines, which was greatest on canines (~10.0deg), followed by lateral incisors (~8.0deg), then central incisors (~5.0deg).

On the first and second molars, mesio-lingual crown displacement and lingual root torque was produced (Figure 3.4). Mesial root tipping movement was also produced, which was greater on the second molars by almost three-fold.
Table 3.2 Tooth movement in 6DoF, produced by the archwire with the reversed curve of Spee

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Central Incisor</th>
<th>Lateral Incisor</th>
<th>Canine</th>
<th>First Premolar</th>
<th>Second Premolar</th>
<th>First Molar</th>
<th>Second Molar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>31</td>
<td>41</td>
<td>32</td>
<td>42</td>
<td>33</td>
<td>43</td>
<td>34</td>
</tr>
<tr>
<td>Translation (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mes</td>
<td>0.6 ± 1.2</td>
<td>0.1 ± 0.6</td>
<td>0.9 ± 0.3</td>
<td>1.3 ± 1.2</td>
<td>1.5 ± 0.8</td>
<td>0.4 ± 0.9</td>
<td>0.7 ± 0.4</td>
</tr>
<tr>
<td>Buc</td>
<td>0.8 ± 0.5</td>
<td>1.1 ± 0.7</td>
<td>0.9 ± 0.6</td>
<td>0.3 ± 0.1</td>
<td>0.0 ± 0.3</td>
<td>0.3 ± 0.2</td>
<td>0.4 ± 0.2</td>
</tr>
<tr>
<td>Int</td>
<td>0.7 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>0.5 ± 0.3</td>
<td>0.1 ± 0.0</td>
<td>1.3 ± 0.4</td>
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<tr>
<td>Rotation (deg)</td>
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<tr>
<td>Din</td>
<td>0.8 ± 0.7</td>
<td>1.4 ± 1.5</td>
<td>0.9 ± 0.9</td>
<td>0.3 ± 1.7</td>
<td>1.2 ± 0.7</td>
<td>1.0 ± 1.4</td>
<td>1.7 ± 2.7</td>
</tr>
<tr>
<td>Dout</td>
<td>10.6 ± 3.1</td>
<td>11.8 ± 3.2</td>
<td>8.1 ± 2.7</td>
<td>8.8 ± 2.8</td>
<td>1.5 ± 1.5</td>
<td>1.4 ± 1.4</td>
<td>0.7 ± 1.1</td>
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<tr>
<td>Torque (deg)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>RtLin</td>
<td>6.5 ± 3.8</td>
<td>1.1 ± 1.5</td>
<td>9.6 ± 2.0</td>
<td>6.8 ± 1.7</td>
<td>10.3 ± 2.5</td>
<td>9.5 ± 3.8</td>
<td>7.9 ± 2.2</td>
</tr>
<tr>
<td>RtLab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RtMes</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RtDis</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Data are presented as means and standard deviations.

Direction of movement for each tooth are orientated by the attached bracket, with the estimated Centre of Resistance as the landmark.


DoF, Degrees of Freedom; Mes, mesial; Dx, distal; Buc, buccal; Lin, lingual; Int, intrusion; Ext, extrusion; Din, distal-in; Dout, distal-out; RtLin, root lingual; RtLab, root labial; RtMes, root mesial; RtDis, root distal.

**Figure 3.3.** Lateral view (left) of average tooth movements for each tooth produced by archwires with a reversed curve of Spee.
Figure 3.4. Tooth movement produced by archwires with a reversed curve of Spee. A, occlusal view of the average tooth movement. B, raw data of tooth movement produced by the reversed curve of Spee.
3.5 Discussion

In this study, a stepwise procedure to transfer 3D information from a physical typodont to a digital environment was developed, tested, and successfully implemented. Using a specific combination of hardware and software, we could reliably describe 3D tooth displacement following an archwire adjustment with 6DoF. The effects of an archwire with a reverse curve of Spee on the entire mandibular arch were tested and quantified using this system.

The orthodontic wax-typodont is a simple tool that is widely used both in teaching institutions to study orthodontic biomechanics, as well as for research purposes. However, the tool has a number of shortcomings. Firstly, the magnitude of tooth movement observed in wax-typodonts can markedly differ from the actual movements occurring in-vivo, since the wax does not reflect the biological responses of periodontal and soft tissues structures.

Secondly, differential rates of tooth movement are commonly produced at different depths of the wax arch. Thirdly, it is common for the shape of the wax-arch to deform during the experiments.

This investigation commenced with a pilot study to better understand the above-mentioned limitations, and to optimise the wax-typodont. While biological inaccuracies could not be addressed, previous reports have shown that the movements produced in typodonts were comparable to those occurring in-vivo (Clifford et al., 1999).

To ensure a uniform rate of tooth movement at different depths of the wax arch, other studies have attempted various modifications to the conventional typodont. The Calorific Machine System involved applying heat directly to the teeth, causing the wax to soften evenly around
the individual tooth roots (Rhee et al., 2001). Others have used gelatine as the base material, which undergoes time-dependent deformation under mechanical loading (Clifford et al., 1999). However, both methods require a sophisticated hardware setup and/or special materials. In this study, the wax-arch was designed to have uniform wax thickness surrounding roots of the typodont teeth, to ensure consistency of temperature across the full thickness of the wax during heating. This produced movements very similar to those observed in a gelatine model, when testing the archwire with a reverse curve of Spee (Clifford et al., 1999).

Conventional typodonts frequently experience wax-arch disintegration, and bracket failures during orthodontic archwire activations. In the pilot study, a number of materials were descriptively tested to address these issues. From this preliminary work, a specific wax (i.e. sticky wax) and bonding material (Loctite 406; Henkel, Arizona, USA) were identified. Accordingly, the wax-typodont developed in this study exhibited consistent wax-arch integrity with a wide range of orthodontic activations, with no bond-failures observed throughout the entire study.

Unlike other in-vitro systems used to investigate tooth movements in 3D, such as FEM, the required materials for fabrication of the typodont setup are readily available, and at a reasonable cost. Additionally, the relatively minimal effort and short time required to fabricate makes this a promising tool for future use in research and orthodontic education. The system also demonstrated a high degree of reproducibility with low variability (i.e. standard deviations) across repeated measurements, and minimal errors as indicated by the negligible amount of tooth movement resulting from the control wire.
In the current study, three-dimensional tooth movements were described in a Cartesian coordinate system. Previous studies have suggested the use of distance colour mapping (Li, 2014), or finite helical axis (FHA) (Hayashi et al., 2002; Hayashi et al., 2006) to assess three-dimensional tooth movement. However, it is difficult to extrapolate clinically useful information from the results of these two systems. Distance colour mapping is limited to visual analysis of tooth movement, and is difficult to quantify any of the translatory or rotational movements in 6DoF. FHA, on the other hand, describes magnitude and direction of movements along a specific axis, which can be difficult to interpret into familiar terms.

With the use of Cartesian coordinate system, the tooth movements could be easily described as translation in all three planes, as well as the tipping, torquing and rotational movements for each tooth. Therefore, the displacement can be assessed, and visually appreciated in such a way that is clinically meaningful.

Previous studies have used coronal landmarks (e.g. cusp tips) to measure tooth displacement (Ashmore et al., 2002; Hayashi et al., 2006; Hinterkausen et al., 1998; Yamamoto et al., 1991). Such measurements are influenced by simple tipping movements, and may not be adequate to define the true displacement of a tooth (Koo et al., 2017). Instead, the CoR is considered a reasonable landmark to define tooth displacement, as it is not affected by tipping movements (Koo et al., 2017; Melsen et al., 1989). While this study attempted to define tooth displacements using CoR as the landmark, accurate positioning of the CoR was not an objective of the study. This was deemed unnecessary as the position of the CoR is dependent on the periodontal support (Kuhlberg and Nanda, 2005) that cannot be reproduced in a typodont. With numerous assumptions involved in locating the CoR, the exact magnitude and the direction of movements for each tooth should be interpreted with caution.
Nevertheless, the movements observed in this study were consistent with those previously reported in both in-vivo and in-vitro studies (Clifford et al., 1999; Mitchell and Stewart, 1973). With the second molars included, the archwire with a reverse curve of Spee produced intrusion of the incisors and second molars. With the three-dimensional assessment, the speculative relative-intrusion resulting from the proclination of incisors and distal crown tipping of the second molars were also confirmed.

Mandibular teeth most frequently affected by root resorption was reported to be the incisors, followed by first molars and second premolars (Brezniak and Wasserstein, 1993). One explanation for this finding is that levelling of the curve of Spee involves significant root movement of these teeth (Clifford et al., 1999). The findings of this study supports this hypothesis as there was significant root movement on the anterior-end (i.e. incisor), and posterior-end (i.e. molar) produced by the archwire with the reverse curve of Spee. Where typical orthodontic treatment does not involve bonding the second molars, significant root movements at the posterior-end would involve second premolar, and first molar teeth. In addition, intrusive movement was noted on the anterior and posterior-ends of the arch with the use of a reverse curve of Spee archwire. It has also been reported that such intrusive movements may significantly increase the risk of root resorption (Harris, 2000).

Toe-in curves in the molar region are often found in the commercially available Nickel Titanium wires with a reverse curve of Spee. These curves are often necessary for distal-in rotation of the molars (McLaughlin et al., 2002). However, as far as we are aware the effects of such toe-in curves on tooth movements have not previously been reported. The archwire with a reverse curve of Spee used in this study had the toe-in curve incorporated, which
produced distal-in rotation of the first and second molar teeth, as well as the second premolar teeth. Marked lingual crown displacement were also produced on these teeth. These movements cannot be attributed to the toe-in curves alone without ruling out the possible confounding effects from the reverse curve of Spee. Nevertheless, the use of the reverse curve of Spee wire with the toe-in curve must be used with caution, especially when used in conjunction with other mechanics that could amplify the lingual displacement. A common example would be the use of inter-maxillary Class II elastics, with its lingual crown displacement effect on the mandibular molar teeth, although validation of this effect is required.

In a clinical setting, an archwire with a reverse curve of Spee is often used to level an occlusion with a curve of Spee. To mimic this situation, an ideal baseline occlusion of the experiment would have been a mandibular arch with an existing curve of Spee. However, fabricating a baseline occlusion with a curve of Spee is difficult without introducing error. Previously, baseline occlusions have been constructed using an archwire with a built-in curve of Spee (Clifford et al., 1999). The resultant occlusion lacked root parallelism, which may have occurred due to torqueing of anterior teeth, and root tipping of the posterior teeth. Since it was difficult to consistently reproduce a standardised occlusion without introducing such errors, we considered a baseline occlusion with a flat occlusal plane.

Archwires with a reverse curve of Spee are reported to increase the arch-length, via anterior displacement of the incisors and posterior displacement of the molars (Clifford et al., 1999; Mitchell and Stewart, 1973). In our study, posterior displacement of the incisors was produced instead (although this was masked by simultaneous proclination), as well as
anterior displacement of the molars. Such effects are likely to have been caused by reduced arch-length produced by introducing a reverse curve of Spee into a flat occlusal plane.

In future studies, the standardised baseline occlusion with an existing curve of Spee may be considered with the aid of CAD/CAM assisted wire-bending. Using such a baseline setup, the arch-length implications can be investigated with improved clinical relevance. Furthermore, the effect of using a reverse curve archwire without toe-in curve in the molar region, or a round wire with a reverse curve could also be studied for an improved understanding of this activation.

Current use of statically indeterminate mechanics is mostly speculative, since the predictability of resultant movements is poor. Within the limitations of the optimised typodont system, this model provides a novel method to assess the effect of common orthodontic activations that are statically indeterminate. Due to its simplicity and cost-effectiveness, this may be a promising tool in tertiary institutions to study orthodontic biomechanics.
3.6 Conclusion

The optimised typodont system was developed and could reliably be used to quantify tooth movement in three-dimensions. Archwires with a reverse curve of Spee have 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd} order implications which should be taken into account when planning treatment.
3.7 References


Chapter 4 – Archform Reshaping

Abstract

Introduction

Materials and Methods

Results

Discussion

Conclusions

References
4.1 Abstract

**Background:** During conventional orthodontic treatment, archwires are often reshaped to coordinate the maxillary and mandibular archforms. Such reshaping activation involve selective expansion and constriction across sections of the wire which are statically indeterminate, and their effects on the whole arch can be difficult to predict.

**Aim:** The aim of this study was to assess three-dimensional tooth movements resulting from various archwire reshaping activations.

**Methods:** A *optimised typodont system* was used to test the following archwire modifications, on the entire mandibular dental arch:

- Posterior expansion
- Creating a more squared shape
- Creating a more tapered shape
- Producing an asymmetry in the arch form

Each archwire activation was repeated three times, and the resulting three-dimensional movement of individual teeth were assessed with six degrees of freedom.

**Results:** Squaring and expanding the archform produced arch-width expansion via *controlled tipping*, centred around premolars and second molars respectively. Tapering the archform constricted the arch-width via *controlled tipping* centred around first premolars.

Squaring and expanding the archform were accompanied with retraction of the anterior teeth, whereas tapering the archform resulted in proclination. The transverse-to-sagittal movement
ratio ranged from 2:1 to 7:1 depending on the activation. An asymmetrical archform caused a shift in the midline (~1.5mm) and a change in the lateral overjet pattern.

**Conclusion:** Archwire recontouring adjustments have both transversal and sagittal implications that should be taken into account when planning orthodontic tooth movement. Asymmetrical reshaping may be used in selected cases for the correction of asymmetrical archforms, with the potential in correcting both the midline and lateral overjet pattern.
4.2 Introduction

During conventional fixed appliance orthodontic treatment, maintenance of the original dental archform and arch width is generally recommended to improve post-treatment stability (Burke et al., 1998; de la Cruz et al., 1995). Nonetheless, reshaping of the archform is often necessary to coordinate maxillary and mandibular archforms, especially in cases with crossbites or scissors-bites (Lee, 1999; McLaughlin et al., 2002). An intermaxillary archform discrepancy may result from an underlying skeletal cause, thus requiring orthopaedic or surgical treatment. However, they may also result from dentoalveolar causes such as asymmetric mechanics (e.g. unilateral intermaxillary elastics) or asymmetric extractions (Dahiya et al., 2017), which often require reshaping of an archwire (McLaughlin et al., 2002).

An archwire may be reshaped via selective expansion or constriction, depending on the presenting malocclusion and desired tooth movement. However, archwire reshaping adjustments are statically indeterminate and their effects can be difficult to predict (Lindauer, 2001). While the transverse effects of wire expansion at the molars are well documented (Kraus et al., 2014; McNally et al., 2005), the effects at the premolars and incisors remain largely speculative. Other widely used archform modifications such as those that have been constricted or made asymmetrical, have not been investigated and the accompanying movements are still poorly understood. With experimental dental simulations, the likely movements from such activations can be better understood, thus improving the predictability and efficiency of their use.
The aim of this study was to assess three-dimensional tooth movement that may result from archwire reshaping, including posterior expansion, squaring, tapering, and asymmetrical activation.

4.3 Materials and Methods

The optimised typodont system was used to investigate the effects of four different archwire reshaping activations (i.e. expanding of molars, squaring, tapering, and asymmetrical) on the entire mandibular arch (Figure 4.1). A passive non-contoured archwire was also tested as a control.

Details concerning the development of the optimised typodont system are described earlier in Sections 2.2 - 2.8 of Chapter 2. In brief, an optimised wax-typodont was assembled using a master stent that could be used to test an orthodontic arch wire activation. The 3D information obtained from the optimised typodont could be easily transferred to the digital environment, where the resultant movements could be analysed with 6DoF.

Archwires from the same supplier with four different contours were tested and included:

- expansion of 4mm on each side at the level of first molars (Permachrome – Ovoid; 3M, Minnesota, USA);
- squaring to widen between premolars,
- tapering to narrow between canines; and,
- asymmetrical reshaping with the vertex of the parabola located at lower right canine.

Archwires used to construct the baseline setup were used without recontouring as the control.
wire.

The archwires were standardised by using three default archforms from the manufacturer where possible (i.e. ovoid, tapered, and squared). For the expanded and asymmetrical adjustments, a printed archform template was prepared by scanning a recontoured 0.019 x 0.025-inch stainless steel archwire. The recontoured wire for the expanded arch was prepared by pulling the two ends of the wire away from each other, resulting in an expansion of 4mm at the midpoint of the molar tube on both the left and right first molars. The recontoured asymmetrical wire was prepared to have the vertex of the parabola located at the lower right canine.
Figure 4.1. Tested archforms. A. baseline (control) archform. B. tapered, with reduced intercanine width. C. squared, with increased inter premolar width. D. an expansion of 4mm added on each side at the level of first molars. E. asymmetrical archform with the vertex of the parabola located at lower right canine.
Experimental procedure

All the experimental tests were conducted in the postgraduate research bench space at the University of Otago, at a room temperature of 22 ± 2°C as measured using a digital thermometer (Brannan, Cumbria, England).

A water bath with a variable temperature range between 30 - 80°C (Whip Mix, Kentucky, USA) was prepared and placed into an insulating box to minimise variations in the temperature (Polybin; Long Plastics, Christchurch, New Zealand). A digital thermometer (Brannan, Cumbria, England) placed in the water bath was also used to monitor and adjust the temperature as required.

The baseline typodont setup was prepared as detailed in Sections 2-3 and 2-4 of Chapter 2. In brief, the optimised typodont was setup using a master stent, and a 0.019 x 0.025-inch stainless archwire (Permachrome - Ovoid; 3M, Minnesota, USA) was engaged using elastomeric modules (Mini-Stik™; 3M, Minnesota, USA). The typodont was heated in the water bath at 44 ± 1°C for 90 minutes. The temperature and time required for an active archwire to become passive were determined during a pilot study described in Section 2.5 of Chapter 2. The typodont was then cooled in a cold (5°C) water bath for 5 minutes, digitised using a 3D-scanner (Ceramill Map400; Amann Girrbach, Koblach, Austria), and saved in a stereolithography (STL) file format as the baseline setting (T0).

One of the activation archwires was then engaged into the prepared typodont using elastomeric modules, and heated in the water bath (44 °C ± 1 °C) for 90 minutes. The typodont was then cooled in a cold (5°C) water bath for 5 minutes, digitised using a 3D-
scanner, and saved again in a STL file format (T₁-activation). This procedure was repeated for each activation archwire (i.e. expanding the molars, squaring, tapering, asymmetrical) and the control.

Each of the four activation archwires and the control archwire were tested three times, for a total of fifteen experiments. Each experiment was carried out on a separate day at the same time (6:00pm) in a random order by the same researcher (AK). All the experiments were completed within 30 days.

Assessment of tooth movement

Details regarding the assessment of tooth movements are described in Sections 2.7 and 2.8 of Chapter 2. Briefly, the digitised typodont setups obtained before (T₀) and after (T₁) each activation were registered using the rigid base as the fiducial marker. The change in the position of each tooth from T₀ to T₁ was assessed using 6DoF in the Cartesian coordinate system. The axes of the system were orientated so that the x-axis represented mesio-distal, y-axis represented bucco-lingual, and z-axis represented intrusive-extrusive directions, for each tooth.

The mesio-distal, bucco-lingual, and intrusive-extrusive movements were assessed as changes in the location of CoR from T₀ to T₁ in the x, y, z axes, respectively. The torque, tip, and rotation movements were assessed as the rotations around the mesio-distal, bucco-lingual, and intrusive-extrusive axes, respectively.

Data analysis
Data were analysed using conventional descriptive statistics. The mean and standard deviations of tooth displacements were calculated for individual teeth using Excel spreadsheets (Office 365 ProPlus; Microsoft, Washington, USA). The results from all typodont activations were first analysed individually, and then averaged for each test and control archwire activations. No inference tests were carried out due to the descriptive nature of the study.
4.4 Results

4.4.1 Control Activation

The control wire produced minimal movements in all directions (Figure 4.2). The translation of all teeth were less than 0.1mm in all three dimensions, while rotation, torque and tip were less than 0.8° (Table 4.1). There was minimal variation between the three repeats of the activation as represented by the low standard deviations.
Table 4.1 Tooth movement in 6DoF, produced by the control wire

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Translation (mm)</th>
<th>Rotation (deg)</th>
<th>Torque (deg)</th>
<th>Tipping (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mes</td>
<td>Dis</td>
<td>Buc</td>
<td>Lin</td>
</tr>
<tr>
<td></td>
<td>0.0 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>0.1 ± 0.0</td>
<td>0.1 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>0.1 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td></td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td></td>
<td>0.2 ± 0.2</td>
<td>0.1 ± 0.3</td>
<td>0.7 ± 0.5</td>
<td>0.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>0.3 ± 0.2</td>
<td>0.2 ± 0.2</td>
<td>0.4 ± 0.3</td>
<td>0.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>0.1 ± 0.3</td>
<td>0.0 ± 0.2</td>
<td>0.8 ± 0.1</td>
<td>0.2 ± 0.3</td>
</tr>
</tbody>
</table>

Data are presented as means and standard deviations. Direction of movement for each tooth are orientated by the attached bracket, with the estimated Centre of Resistance as the landmark. Unshaded cells represent movement in the mesial / buccal / intrusive / distal-in / root-lingual / root-mesial direction. Shaded cells represent movement in the distal / lingual / extrusive / distal-out / root-labial / root-distal direction.

DoF: Degrees of Freedom; Mes, mesial; Dis, distal; Buc, buccal; Lin, lingual; Int, intrusion; Ext, extrusion; Din, distal-in; Dout, distal-out; RtLin, root lingual; RtLab, root labial; RtMes, root mesial; RtDis, root distal.

**Figure 4.2.** Tooth movement produced by the control wire. **A.** average tooth movement for each tooth. **B.** raw data of tooth movement from all three repeats.
4.4.2 Archwire Activation

(1) Expanded archwire

Movements produced by the expanded archwire are presented in Table 4.2 and Figure 4.3. There was minimal variation between the three repeats for this activation.

The expanded archwire produced expansion (i.e. buccal displacement) of the premolars and molars. Expansion was greatest between the second molars (~2.2mm), followed by first molars, second premolars, and then first premolars (~0.5mm). Expansion via controlled tipping of the molars was observed, as indicated by a change in their root lingual torque (i.e. buccal crown torque, with a centre of rotation close to the apex).

In the anterior region, the expanded archwire caused a small retraction of the incisors. Retraction was slightly greater at the central incisors than of the lateral incisors.

When comparing the expansion between the second molars (i.e. increase in arch-width) to the retraction of the central incisors, the transversal-to-incisal movement ratio was approximately 7:1.

A slight distal-out rotation (less than 3.4 deg) was produced on all the teeth in the arch.
Table 4.2 Tooth movement in 6DoF, produced by the expanded archform

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Translation (mm)</th>
<th>Rotation (deg)</th>
<th>Torque (deg)</th>
<th>Tipping (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>37</td>
<td>36</td>
<td>35</td>
<td>34</td>
</tr>
<tr>
<td>Mes Dis</td>
<td>0.0 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>0.0 ± 0.2</td>
<td>0.1 ± 0.2</td>
</tr>
<tr>
<td>Buc Lin</td>
<td>1.1 ± 0.3</td>
<td>0.8 ± 0.2</td>
<td>0.5 ± 0.3</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Int Ext</td>
<td>0.3 ± 0.2</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td></td>
<td>0.9 ± 0.4</td>
<td>2.2 ± 0.1</td>
<td>2.1 ± 1.2</td>
<td>2.5 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>59 ± 2.0</td>
<td>4.0 ± 1.2</td>
<td>2.4 ± 0.4</td>
<td>1.6 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>0.5 ± 0.4</td>
<td>0.6 ± 0.3</td>
<td>1.1 ± 0.6</td>
<td>1.3 ± 0.6</td>
</tr>
</tbody>
</table>

Data are presented as means and standard deviations. Direction of movement for each tooth are orientated by the attached bracket, with the estimated Centre of Resistance as the landmark. Unshaded cells represent movement in the mesial / buccal / intrusive / distal-in / root-lingual / root-mesial direction. Shaded cells represent movement in the distal / lingual / extrusive / distal-out / root-labial / root-distal direction.

DoF, Degrees of Freedom; Mes, mesial; Dis, distal; Buc, buccal; Lin, lingual; Int, intrusion; Ext, extrusion; Din, distal-in; Dout, distal-out; RtLin, root lingual; RtLab, root labial; RtMes, root mesial; RtDis, root distal.

Figure 4.3. Tooth movement produced by expanded archwire activation. A, average tooth movement for each tooth. B, raw data of tooth movement from all three expanded archwire activation repeats.
**(2) Squared archwire**

Tooth movement produced by the squared archwire are detailed in Table 4.3 and Figure 4.4. There was minimal variation between the three repeats for this activation.

The squared archwire produced expansion (i.e. buccal displacement) of canine, premolar and first molar teeth. Expansion was greatest between the first and second premolars (~1.0mm), followed by first molars (~0.5mm) and canines (~0.2mm). Expansion of the premolars occurred via *controlled tipping* as indicated by the change in their root lingual torque (i.e. buccal crown torque with a centre of rotation close to the apex).

In the anterior region, the incisor teeth were slightly retracted. Retraction was greater on the central incisors than the lateral incisors.

All the anterior teeth and the first premolars exhibited distal-out rotation, which was greatest on the canines (~3.5 deg). All other posterior teeth exhibited distal-in rotation, which was greatest on the second premolars (~2.0 deg).

The transversal-to-incisal movement ratio was approximately 3:1, when comparing the greatest expansion between first and second premolars to the greatest retraction of the central incisors.
### Table 4.3 Tooth movement in 6DoF, produced by the squared archform

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Translation (mm)</th>
<th>37</th>
<th>36</th>
<th>35</th>
<th>34</th>
<th>33</th>
<th>32</th>
<th>31</th>
<th>32</th>
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<th>37</th>
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<tr>
<td></td>
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<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.2 ± 0.2</td>
<td>0.3 ± 0.1</td>
<td>0.2 ± 0.2</td>
<td>0.0 ± 0.2</td>
<td>0.3 ± 0.2</td>
<td>0.1 ± 0.2</td>
<td>0.0 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Buc Lin</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>0.0 ± 0.3</td>
<td>0.2 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>0.5 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>0.2 ± 0.1</td>
<td>0.1 ± 0.0</td>
<td>0.5 ± 0.1</td>
<td>0.6 ± 0.0</td>
<td>0.3 ± 0.1</td>
<td>0.2 ± 0.2</td>
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</tr>
<tr>
<td></td>
<td>Int Ext</td>
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<td></td>
<td>0.0 ± 0.1</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>0.0 ± 0.1</td>
<td>0.0 ± 0.0</td>
<td>0.2 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Rotation (deg)</th>
<th>Din</th>
<th>Dout</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mes Dis</td>
<td>0.4 ± 0.1</td>
<td>1.4 ± 0.8</td>
<td>2.1 ± 1.7</td>
<td>2.9 ± 1.0</td>
<td>2.9 ± 1.3</td>
<td>2.3 ± 0.1</td>
<td>0.9 ± 0.3</td>
<td>0.7 ± 0.3</td>
<td>2.5 ± 0.3</td>
<td>4.0 ± 0.6</td>
<td>3.1 ± 0.3</td>
<td>1.6 ± 0.7</td>
<td>0.7 ± 0.6</td>
<td>0.2 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>Buc Lin</td>
<td>0.6 ± 0.9</td>
<td>1.1 ± 0.5</td>
<td>2.5 ± 0.8</td>
<td>2.0 ± 0.7</td>
<td>1.1 ± 0.3</td>
<td>0.3 ± 0.1</td>
<td>0.0 ± 0.2</td>
<td>0.1 ± 0.2</td>
<td>0.2 ± 0.2</td>
<td>1.2 ± 0.5</td>
<td>2.0 ± 0.6</td>
<td>2.2 ± 0.3</td>
<td>1.2 ± 0.1</td>
<td>1.0 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>Int Ext</td>
<td>0.9 ± 0.6</td>
<td>0.8 ± 0.3</td>
<td>0.4 ± 0.3</td>
<td>0.6 ± 0.4</td>
<td>0.7 ± 0.5</td>
<td>0.5 ± 0.3</td>
<td>0.2 ± 0.6</td>
<td>0.2 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>1.8 ± 0.8</td>
<td>0.8 ± 0.5</td>
<td>0.6 ± 0.5</td>
<td>0.9 ± 0.2</td>
<td>0.6 ± 0.2</td>
</tr>
</tbody>
</table>

Data are presented as means and standard deviations. Direction of movement for each tooth are orientated by the attached bracket, with the estimated Centre of Resistance as the landmark. Unshaded cells represent movement in the mesial / buccal / intrusive / distal-in / root-lingual / root-mesial direction. Shaded cells represent movement in the distal / lingual / extrusive / distal-out / root-labial / root-distal direction.

*DoF*, Degrees of Freedom; *Mes*, mesial; *Dis*, distal; *Buc*, buccal; *Lin*, lingual; *Int*, intrusion; *Ext*, extrusion; *Din*, distal-in; *Dout*, distal-out; *RtLin*, root lingual; *RtLab*, root labial; *RtMes*, root mesial; *RtDis*, root distal.

**Figure 4.4.** Tooth movement produced by squared archwire activation. **A**, average tooth movement for each tooth. **B**, raw data of tooth movement from all three squared archwire activation repeats.
(3) Tapered archwire

Tooth movements produced by the tapered archwire are presented in Table 4.4 and Figure 4.5. There was minimal variation between the three repeats for this activation. Movements produced by the tapered archwire were generally opposite to the movements produced by the squared archwire.

The tapered archwire produced constriction (i.e. lingual displacement) of canine, and premolar teeth. Constriction was greatest between the first premolars (~1.3mm), followed equally by the canines and second premolars (~0.5mm). The constriction of premolars and canines was the result of a controlled tipping movement, as indicated by changes in their labial root torque (i.e. lingual crown torque with a centre of rotation close to the apex).

Anterior displacement occurred at the incisors, which was greater at the central incisors (~0.7mm) than the lateral incisors (~0.3mm).

The transversal-to-incisal movement ratio was approximately 2:1, when comparing the greatest constriction between the first premolars to the anterior displacement of the central incisors.

Distal-in rotation was produced on all the anterior teeth, which was greatest on the canines (~6.0deg). Distal-out rotation occurred at the premolars and first molars, but was greatest at the second premolars (~3.0deg).
Table 4.4 Tooth movement in 6DoF, produced by the tapered archform

<table>
<thead>
<tr>
<th>Translation (mm)</th>
<th>Tooth</th>
<th>37</th>
<th>36</th>
<th>35</th>
<th>34</th>
<th>33</th>
<th>32</th>
<th>31</th>
<th>41</th>
<th>42</th>
<th>43</th>
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<tbody>
<tr>
<td>Mes</td>
<td>Dis</td>
<td>0.2±0.0</td>
<td>0.1±0.1</td>
<td>0.2±0.0</td>
<td>0.1±0.1</td>
<td>0.5±0.1</td>
<td>0.4±0.4</td>
<td>0.3±0.3</td>
<td>0.3±0.3</td>
<td>0.5±0.1</td>
<td>0.5±0.1</td>
<td>0.0±0.1</td>
<td>0.1±0.1</td>
<td>0.0±0.1</td>
<td>0.0±0.1</td>
</tr>
<tr>
<td>Buc</td>
<td>Lin</td>
<td>0.3±0.4</td>
<td>0.2±0.2</td>
<td>0.2±0.1</td>
<td>0.6±0.1</td>
<td>0.2±0.1</td>
<td>0.4±0.4</td>
<td>0.1±0.1</td>
<td>0.7±0.1</td>
<td>0.7±0.1</td>
<td>0.3±0.2</td>
<td>0.3±0.2</td>
<td>0.7±0.2</td>
<td>0.4±0.1</td>
<td>0.1±0.2</td>
</tr>
<tr>
<td>Int</td>
<td>Ext</td>
<td>0.0±0.1</td>
<td>0.0±0.1</td>
<td>0.1±0.1</td>
<td>0.1±0.1</td>
<td>0.0±0.1</td>
<td>0.0±0.1</td>
<td>0.0±0.1</td>
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<td>0.0±0.1</td>
<td>0.0±0.1</td>
<td>0.0±0.1</td>
<td>0.0±0.1</td>
<td>0.0±0.1</td>
</tr>
<tr>
<td>Rotation (deg)</td>
<td>Din</td>
<td>0.0±0.5</td>
<td>2.0±1.3</td>
<td>3.6±1.8</td>
<td>1.8±1.9</td>
<td>6.0±1.3</td>
<td>4.7±1.5</td>
<td>2.3±1.4</td>
<td>0.8±0.6</td>
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<td>5.5±0.8</td>
<td>2.2±1.6</td>
<td>2.9±1.5</td>
<td>1.2±1.4</td>
<td>0.4±1.2</td>
</tr>
<tr>
<td>Torque (deg)</td>
<td>Dout</td>
<td>0.5±1.5</td>
<td>0.8±1.1</td>
<td>0.1±1.0</td>
<td>0.8±0.7</td>
<td>1.1±0.9</td>
<td>0.2±0.7</td>
<td>0.3±0.6</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
<td>0.0±0.0</td>
<td></td>
</tr>
<tr>
<td>Tipping (deg)</td>
<td>RtLin</td>
<td>0.5±0.2</td>
<td>0.2±0.2</td>
<td>0.7±0.1</td>
<td>0.8±0.9</td>
<td>0.7±0.4</td>
<td>1.1±0.6</td>
<td>1.3±1.0</td>
<td>0.6±0.8</td>
<td>2.6±1.7</td>
<td>2.4±1.0</td>
<td>0.5±0.5</td>
<td>0.3±1.0</td>
<td>0.1±0.2</td>
<td>0.1±0.5</td>
</tr>
<tr>
<td></td>
<td>RtLab</td>
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</tr>
<tr>
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<td></td>
</tr>
<tr>
<td></td>
<td>RtDis</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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</tr>
</tbody>
</table>

Data are presented as means and standard deviations.
Direction of movement for each tooth are orientated by the attached bracket, with the estimated Centre of Resistance as the landmark.

DoF, Degrees of Freedom; Mes, mesial; Dis, distal; Buc, buccal; Lin, lingual; Int, intrusion; Ext, extrusion; Din, distal-in; Dout, distal-out; RtLin, root lingual; RtLab, root labial; RtMes, root mesial; RtDis, root distal.

Figure 4.5. Tooth movement produced by tapered archwire activation. A, average tooth movement for each tooth. B, raw data of tooth movement from all three tapered archwire activation repeats.
(4) Asymmetrical archwire

Tooth movements produced by the tapered archwire are presented in Table 4.5 and Figure 4.6. There was minimal variation between the three repeats for this activation.

The asymmetrical archwire produced a shift in the midline (~1.5mm) towards the vertex of the parabola. Midline shift was mostly from tipping and minimal root movement, as indicated by mesial root tipping (i.e. distal crown tipping) of the incisors on the vertex side (~4.5deg), and distal root tipping (i.e. mesial crown tipping) of the incisors on the contralateral side (~3deg).

On the side of the vertex (i.e. right), expansion was produced on the incisor, canine, and premolar teeth. On the other hand, constriction was produced on the contralateral side, involving the same teeth. The greatest transversal changes (i.e. expansion or constriction) was produced on the canines and lateral incisors (~1.2mm), followed by the first premolars and central incisors.

On the vertex side, both the first and second molars exhibited constriction (~0.5 - 1.0mm) via controlled tipping (i.e. accompanying buccal root torque, or lingual crown torque). Conversely, expansion (~1 - 2mm) via controlled tipping (i.e. accompanying buccal root torque, or lingual crown torque) was observed at the first and second molars on the side opposite the vertex.

On the vertex side, the central incisor rotated in a distal-in direction (~9.5deg), whereas the canine and all other posterior teeth rotated in the distal-out distection (~5deg). Rotations of all teeth ipsilateral to the vertex were opposite to those contralateral.
Table 4.5 Tooth movement in 6DoF, produced by the asymmetrical archform

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Translation (mm)</th>
<th>Rotation (deg)</th>
<th>Torque (deg)</th>
<th>Tipping (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Din</td>
<td>Dout</td>
<td>RtLin</td>
</tr>
<tr>
<td>Mes</td>
<td>Dis</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>0.8 ± 0.1</td>
<td>0.7 ± 0.0</td>
<td>0.8 ± 0.2</td>
<td>0.8 ± 0.3</td>
</tr>
<tr>
<td>Buc</td>
<td>Lin</td>
<td></td>
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<td>1.9 ± 0.8</td>
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<td>9.5 ± 1.6</td>
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<td>2.2 ± 1.8</td>
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<td>3.5 ± 0.8</td>
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Data are presented as means and standard deviations.

Direction of movement for each tooth are orientated by the attached bracket, with the estimated Centre of Resistance as the landmark.


DoF: Degrees of Freedom; Mes, mesial; Dis, distal; Buc, buccal; Lin, lingual; Int, intrusion; Ext, extrusion; Din, distal-in; Dout, distal-out; RtLin, root lingual; RtLab, root labial; RtMes, root mesial; RtDis, root distal.

Figure 4.6. Tooth movement produced by asymmetrical archwire activation. A, average tooth movement for each tooth. B, raw data of tooth movement from all three asymmetrical archwire activation repeats.
4.5 Discussion

Distinctive tooth movement produced by a number of archwire recontouring adjustments were analysed in this study. To the best of our knowledge, no previous study has investigated tooth movement produced by such archwire reshaping activations.

Expanded, squared, tapered reshaping

The reshaping activations in this study could simply be characterised as either a widening or narrowing of the archwire, at various anterior-posterior locations. The expanded archwire was widened across the second molars, whereas the squared archwire was widened between the premolars. The tapered archwire was narrowed between the canine/first premolar region. Depending on both the type and location of the reshaping, there were implications for arch-width changes and incisal tooth movement.

In general, the arch-width seemed to increase as the archwire was widened, and vice versa. Thus, an expanded archwire (i.e. widened between the second molars) produced the greatest arch-width increase across the second molars, and progressively lesser towards the anterior segments. The squared archwire (i.e. widened between the premolars) produced the greatest arch-width increase across the premolars. On the other hand, the tapered archwire (i.e. narrowed between canines/first premolars) produced a decrease in the arch-width between the canines and first premolars. These results suggest that careful reshaping of the archform may help correct transverse issues, such as posterior cross-bites and scissor-bites.

Incisors position was also affected by the reshaping of the arch form. With the expanded archwire (i.e. widening between second molars), incisor retraction was consistently
produced with a transversal-to-incisal movement ratio of approximately 7:1. Based on this ratio, a typical molar expansion of approximately 4mm would retract the incisors by 0.5mm. While this has some implications on the resultant overjet, its clinical significance is still questionable. Nonetheless, the retraction tendency associated with the expanded wire should be considered during the careful planning of treatment mechanics.

The squared archwire (i.e. widening between premolars) also produced incisor retraction, but with a transversal-to-incisal movement ratio of 3:1. In this situation, a 4 mm expansion between the premolars would retract the incisors by approximately 1.3mm, which may have a greater impact on the overjet compared to the expanded archwire. Where a squared archwire is indicated for coordination of the maxillary and mandibular archforms, the impact of this activation on the incisors should be carefully considered.

On the other hand, the tapered arch-wire (i.e. narrowing between canines and first premolars) produced anterior displacement of incisors, with a transversal-to-incisal movement ratio of 2:1. This activation had the greatest influence on the overjet, with constriction between the premolars of approximately 4mm has the potential to procline the incisors by approximately 2mm.

The findings from this study indicate that the magnitude of the incisal movement is associated with the anterior-posterior location of the archwire reshaping. When tooth movement produced by the tapered, squared, and expanded archwires are considered collectively, it is clear that the incisal movements were greater when the reshaping was located further anteriorly (i.e. tapered, followed by squared, then expanded). Although we have shown that narrowing of the archwire may influence the incisors more so than widening
activations, further research is necessary to confirm this observation.

While the expanded archwire increased the intermolar width, the change in the intercanine width was negligible. Interestingly, previous research found that an expansion arch increased both the intermolar and intercanine widths (McNally et al., 2005). This contradiction may have resulted from the difference in the method of ‘expansion’, as the expansion arch in their study included an auxiliary expansion wire in addition to the base archwire. Based on this set-up, it is possible that the active base archwire may have resulted in some increase of the intercanine width.

Previous meta-analysis has highlighted the importance of maintaining intercanine width for post-treatment stability (de la Cruz et al., 1995; McLaughlin and Bennett, 1999; Taner et al., 2004). However, most orthodontic treatment is reported to cause an increase in the intercanine width compared to baseline (Taner et al., 2004). In theory, the tapered archwire activation, with its associated lingual canine displacement, may provide some improvements in post-treatment stability. Although the tapered archwire also results in constriction across the premolar teeth, maintenance of interpremolar width has been suggested to be of lesser importance with minimal relapse tendency (McLaughlin and Bennett, 1999). Nevertheless, anterior displacement of the incisors produced by this activation would need to be carefully considered. It is noteworthy, however, that the exact relationship between the different archforms and long-term stability has yet to be investigated.

**Asymmetrical reshaping**

Patients may present with an asymmetrical archform due to congenital or iatrogenic causes
(McLaughlin et al., 2002). Typically, the resulting malocclusion consists of a reduced lateral overjet (i.e. cross-bite tendency of the canines and premolars) on one side, and an increased lateral overjet (i.e. increased distance between the maxillary and mandibular canines and premolars) on the contralateral side. The midline is also shifted towards the side of the reduced lateral overjet. Although asymmetrical reshaping of the archwire has previously been suggested for the correction of asymmetrical archforms (McLaughlin et al., 2002), the resultant movement from this activation have not been previously described.

The asymmetrical archwire used in this study had the vertex of the parabola skewed to the right. This shifted the midline towards the right, while ‘expanding’ the canines and premolars on the right and ‘constricting’ the contralateral teeth on the left. This finding demonstrates the potential to correct both the midlines and lateral overjet pattern of the asymmetrical archform, supporting the suggested use of asymmetrical archwires to treat such cases.

It is noteworthy, however, that this archwire produced asymmetrical movements of the molars by contracting on the right (i.e. ipsilateral to the vertex) and expanding on the left (i.e. contralateral to the vertex). This finding highlights the posterior transversal implications associated with this type of activation, which should be carefully considered and managed accordingly.

**Future directions**

When applying posterior expansion to an archwire, the *expansion bend* may be introduced in various ways. In this study, the two ends of the wire were pulled away from each other, so that when the ends of the expanded archwire were pressed back towards the original
archform, the wire matched the original shape. Different methods of expansion may lead to narrowing or widening of the inter-canine width when pressing the wire back towards the original archform (McLaughlin et al., 2002). The results of this study cannot be generalised to all expansion techniques, and further research is needed to investigate the effect of different expansion methods.

4.6 Conclusions

Adjustment of the archform produced a change in the arch-width as well as incisal movement depending on the type and location of the reshaping. Widened archwires produced an increase in the arch-width centred at the reshaped area, and retraction of the incisors. Narrowed archwires decreased the arch-width, while displacing the incisors anteriorly. An asymmetrical archform produced a shift in the midline whilst also changing the lateral overjet pattern. Changes in the archform produced movement of all the teeth in the dental arch, which should be taken into account when planning orthodontic treatment.
4.7 References


Chapter 5 - General Discussion and Conclusions

Summary of the Main Findings

General Limitations

Future Directions

General Conclusions

References
5.1 Summary of the Main Findings

The main objectives of the study were (1) to develop a method for assessing simulated three-dimensional tooth movement on a wax-typodont model; and, (2) to test the model for assessing tooth movement that occur during a number of orthodontic archwire adjustments. The study used CAD/CAM technology to transfer 3D information of the wax-typodont into the digital environment. The simulated movement could then be quantified in three-dimensions with 6-DoF. Using this method, the effect of each of the archwire activations on individual teeth were analysed.

The first objective was to develop a method for assessing three-dimensional tooth movement on a wax-typodont model. The assessments were conducted in the digital environment with the use of 3D hardware and software that are commercially available. This required some modifications to the conventional wax typodont to make it compatible with the digital assessment. The potential sources of error in this method included digital superimposition of the 3D-mesh obtained before (T₀) and after (T₁) orthodontic activations, and between individual 3D tooth models at each of the T₀ and T₁ activations. Overall, error values for all the required superimpositions were low, which confirms the reliability of this digitisation method.

The study then progressed to assess the dental effects of a number of archwire activations. In general, reliability of the results were supported by the minimal variation in the movements between repetitions of an activation (i.e. small standard deviations). Additionally, the effect of any possible confounding variables, such as gravity or lack of standardisation
were minimal, as shown by the minimal movements produced by the control archwire in each case.

The movement produced by the archwire with the reverse curve of Spee were comparable to previous clinical (Mitchell and Stewart, 1973) and experimental trials (Clifford et al., 1999), which reported intrusion of incisors and second molars, as well as extrusion of premolars and first molars. The speculated relative-intrusion resulting from the proclination of the incisors and distal crown tipping of the second molars were confirmed. Therefore, the magnitude of the true-intrusion of the teeth may indeed be minimal, and the excessive tipping of the teeth would require careful considerations during the planning of treatment mechanics.

With first order reshaping activation, several effects were seen on arch-width and incisal movements. The results suggest careful selective reshaping of the archform may help correct transverse issues, such as posterior cross-bites, but also to obtain an ideal overjet during the finishing stages of orthodontic treatment. With regards to incisal movement, the wider archforms that were tested in the study (i.e. expanded, and squared) produced retraction, whereas anterior displacement was observed with the narrower archform (i.e. tapered). The magnitude of these movements were greater when the reshaping was located further anteriorly. In summary, both the overjet and transversal implications of archwire reshaping should be carefully considered in clinical practice.

Asymmetrical activations had previously been suggested for correction of asymmetrical archforms (McLaughlin et al., 2002). Typical features of a malocclusion resulting from an asymmetrical archform include reduced lateral overjet on one side, an increased lateral
overjet on the contralateral side, and a midline discrepancy. The suggested use of an asymmetrical activation in such cases was supported by this study, which has a potential in correcting both the midline and lateral overjet pattern. Nevertheless, there was a tendency for the molars to constrict on the side of the vertex and expand on the contralateral side. Clearly these potential transversal implications require careful consideration in clinical treatment.

5.2 General Limitations

As mentioned earlier in the text, the use of a wax-arch does not reflect the biological response of periodontal and soft tissue structures, as well as dynamic forces resulting from everyday mastication. Therefore, the magnitude of tooth movement observed on a typodont can differ markedly from the actual movements occurring in-vivo. Although the results from an in-vivo clinical trial also produced similar results to those of this study (Mitchell and Stewart, 1973), it was not possible to directly compare findings as full 3D assessment of movement was not used in that study.

An estimated CoR is considered a reasonable landmark to define tooth displacement, as it is not affect by tipping movements (Koo et al., 2017). Therefore, CoR was chosen as the landmark for movement analysis in this study. Its location was estimated to be at two-thirds of the root length for single rooted tooth, and at the level of the furcation for molars based on previous studies (Burstone and Pryputniewicz, 1980; Smith and Burstone, 1984). However, the location of CoR is known to change continuously over the period of an
orthodontic activation, as it is dependent on the periodontal support (Kuhlberg and Nanda, 2005). CoR is also suggested to exist as an axis in 3D space (Viecilli et al., 2013). Therefore, estimating CoR as a single point is an oversimplification which should be taken into account when interpreting these findings.

5.3 Future Directions

During orthodontic treatment, a variety of statically indeterminate mechanics are used to produce tooth movement. However, selection of mechanics for specific movements are largely based on anecdotal evidence, as there is a general lack of data on their effects. Within the limitations of the optimised typodont system, the model provides means to assess the effect of common orthodontic arch wire activations that are statically indeterminate. This would improve the overall predictability of their use, and possibly on the efficiency of orthodontic treatment in general.

5.4 General Conclusions

Given the results obtained throughout the study, the optimised typodont system appears to be a promising teaching tool of orthodontic biomechanics, and a research tool for further analyses. Within the limitations of the optimised typodont system, three-dimensional movements produced in the typodont could be reliably assessed for each tooth with 6DoF.

The following conclusions can be made drawn from this study:
1. With the second molars engaged, an orthodontic archwire with a reverse curve of Spee causes intrusion of the incisor and second molar teeth, as well as extrusion of the premolar and first molar teeth. There is also relative-intrusion produced by the proclination of incisors and distal crown tipping of the second molars.

2. An archwire with a reverse curve of Spee that has incorporated toe-in curve produces distal rotation of the molars, and second premolars, as well as mesio-lingual crown displacement and lingual root torque.

3. Reshaping of an orthodontic arch wire produces changes in arch-width which may help correct transverse issues, such as posterior cross-bites.

4. Incisal movement is produced by the recontouring adjustments. Wider archforms had a tendency to retract the incisors, whereas narrower archforms had a tendency to produce proclination. The magnitude of these incisal movements were greater when the reshaping was located further anteriorly.

5. Asymmetrical archwire activation is supported for the correction of asymmetrical archforms, with the potential in correcting both the midline and lateral overjet pattern. However, there was a tendency for molars to constrict on the side of the vertex and expand on the contralateral side.
5.5 References


Chapter 6 – Appendices

Māori Consultation
6.1 Māori Consultation

Tuesday, 07 June 2016.

Professor Mana Parella,
Faculty of Dentistry - Department of Oral Science,
DUNEDIN.

Tāmaki Kōrero Professor Mana Parella,

According to three-dimensional tooth movement during orthodontic activations using an endodontic

The Ngāi Tahu Research Consultation Committee (the committee) met on Tuesday, 07 June 2016 to discuss your research proposition.

By way of introduction, this response from the Committee is provided as part of the Memorandum of Understanding between Te Rūnanga o Ngāi Tahu and the University. In the statement of principles of the memorandum it states: "Ngāi Tahu acknowledges that the consultation process outlined in this policy provides no power of veto by Ngāi Tahu to research undertaken at the University of Otago". As such, this response is not "approval" or "mandate" for the research, rather it is a mandated response from a Ngāi Tahu appointed committee. This process is part of a number of requirements for researchers to undertake and does not cover other issues relating to ethics, including methodology they are separate requirements with other committees, for example the Human Ethics Committee, etc.

Within the context of the Policy for Research Consultation with Māori, the Committee have consultation on that defined by Justice McGechan:

"Consultation does not mean negotiation or agreement. It means: setting out a proposal not fully decided upon, adequately informing a party about relevant information upon which the proposal is based; listening to what the others have to say with an open mind (in that there is room to be persuaded against the proposal); undertaking that task in a genuine and not cosmetic manner. Reaching a decision that may or may not alter the original proposal."

The Committee acknowledges that this research project is laboratory based on distinction of artificial tooth models; therefore further consultation is not required in this instance, however should the project develop further research the Committee would request that you come back for further consultation.

We wish you every success in your research.

This letter of suggestion, recommendation and advice is current for an 18 month period from Tuesday, 07 June 2016 to 7 December 2017.