Comparing the Curvature of Orthodontic Brackets to the Buccal Inclination of the Second Maxillary Premolar

A Master's full thesis submitted in fulfilment of the requirements for the degree of Magister Scientiae in the faculty of Dentistry, University of the Western Cape.

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Key words

Orthodontic Bracket

Orthodontic Bracket Base

Curvature

Gingival Angle

Mesial Angle

Micro-CT

Angular Difference

Buccal curvature of maxillary premolar

Abstract

Background: The relationship between the curvature of the tooth and the curvature on the corresponding bracket is of vital importance. The closer the curvature of the base to that of the tooth, the closer adaptation it will assume. It will consequently have better adhesion, retention and distribute the forces on the tooth more efficiently in all dimensions. However, there is a lack of literature relating the buccal curvature of the tooth to the curvature of the corresponding orthodontic bracket. This dissertation investigated this relationship with the help of a novel methodology using Micro-Computed Tomography (Micro-CT).

Aim: The aim of the study was to compare the buccal curvatures of the maxillary second premolars with the curvatures of three orthodontic bracket brands using a Micro-CT scanner.

Methodology: The study sample included 33 randomly selected maxillary second premolars from archived orthodontic diagnostic models and corresponding orthodontic brackets from three manufacturers: Bioquick (Forestadent), Innovation (GAC) and Victory Series (3M Unitek). The sample was scanned using a Nikon Metrology XTH 225 ST X-ray micro-computer tomography scanner (Yokohama, Japan) at 100kV with a beam current of 200μA with an exposure of 1fps. The images were analysed on Volume graphics VG Studio max 3.2.5. The curvatures of the brackets at the mesial and gingival margin were isolated and the central angle of these curvatures were recorded in degrees. The corresponding curvature angles on the teeth were also recorded of each bracket. The angles of the brackets and the angles on the teeth were analysed to determine which bracket had the lowest angular difference. The angular differences were compared using a two-way ANOVA and a Bonferroni Pairwise Comparison.

Results: The results of the study showed there to be no standardisation between angulations of the 3 bracket brands. It also confirmed the results in the literature which states the existence of a great variation in curvature between maxillary second premolars. A statistically significant interaction was found between the angles of the 3 brackets and the angles on the teeth $p < 0.0001$. The lowest angular difference for the joint 3 and 4 mm prescriptions at the mesial margin of the brackets was that of Victory

Series -1.623 (±5.920) and Bioquick had the lowest angular difference for the joint prescriptions at the gingival margin 5.836 (±13.580). The difference at the mesial margin between the Victory series and Innovation was -4.494 (SE±1.681); p = 1 and between Victory series and Bioquick was -5.145 (SE±1.681); p = 1. Both were statistically insignificant. The difference between Bioquick and Innovation at the gingival bracket margin was 0.811(SE±1.681); p = 0, the difference between Bioquick and Victory series was 11.908 (SE±1.681); p = 0, both were statistically significant.

Conclusion: The results indicated the best performing bracket at the mesial margin to be that of Victory series. This result was followed by Innovation and Bioquick who were closely matched with no significant difference. The best performing bracket at the gingival margin was Bioquick followed by Victory series and Innovation. The curvature of Innovation greatly underestimated the tooth curvature. The best overall angular difference was that of Victory series.

Declaration

I, the undersigned, Yaseen Fakir, hereby declare that the work contained in this dissertation titled, "Comparing the curvature of orthodontic brackets with the buccal inclination of the second maxillary premolar" is my original work and has not been previously in its entirety or in any part submitted at any university for any degree or examination.

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Definition of Terms

Angular Difference: The difference between the central angle of the bracket minus the central angle of the tooth. This angular difference is an indicator of adaptation.

Bracket Angle: The angular representations of the curvatures determined on the brackets.

Central Angle: The angle that forms when two radii meet at the centre of a circle.

Gingival Curve: The curvature at the gingival margin of the tooth of bracket.

Joint Script: The combined data for teeth measured at 3mm and 4mm script.

Mesial Curve: The curvature at the mesial margin of the tooth or bracket.

Midpoint of Curve: The middle of the isolated curve. Midway between the superior and inferior points.

Standardised Area of Contact: The most probable area of contact between the bracket and the tooth. Represented by a 75% height and 75% width of the bracket. This allow standardisation of orthodontic brackets, irrespective of shape and size.

Target Point of the Bracket: The midpoint of the bracket.

Target Point of Tooth: A point 4 mm of 3 mm from the cusp tip, along the central axis of the clinical crown.

Tooth Angles / Angles of the bracket on the tooth: The curvature angles of the placement of the brackets on the tooth. Each tooth has three sets of “angles on the tooth” to represent the three dimensions of each bracket.

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Chapter 1

Introduction

Dr Edward Angle created the Edgewise system which has provided the concept for subsequent orthodontic bracket systems. The original Edgewise appliances made use of stainless-steel bands to attach the orthodontic brackets to teeth (Moyers, 1988). The brackets were welded to the bands prior to cementation of the bands around the teeth. This was a protracted process for both the clinician and the patient with the bands being unaesthetic and unhygienic. The bands engaged around the tooth, resulting in multiple interdental spaces which required closure post-treatment (Moyers, 1988).

The introduction of the orthodontic bracket adhesion with the advent of acid etching led to dramatic changes in the practice of orthodontics (Komori and Ishikawa, 1999). Bishara et al., (1999) summarised the advantages of bonding the orthodontic brackets as multifactorial namely: ease of plaque control, minimal soft tissue inflammation, absence of post treatment band spaces, the ability to bond to partially erupted teeth, easier monitoring of caries and enhanced aesthetics.

Andrews (1972) created the straight-wire appliance based on the principles of his studies on the "Six Keys of Occlusion" (Andrews, 1972). He modified the Edgewise bracket system to transfer 1st, 2nd and 3rd order bends from wire to brackets. This was done in order to achieve three-dimensional tooth movement and finalization of treatment.

The theory behind the system was that, with all brackets in the optimal position, a pre-shaped arch wire would bring the teeth into a pre-determined arch position. But, this simply was not all that was required to achieve the pre-determined arch position, since the incorrect placement of the bracket has been shown to affect torque delivery and therefore, the tooth movement (Mestriner et al., 2006).

Andrews stated that there existed small variations in dental morphology between individuals and that it would not affect the correct positioning of the bracket (Andrews, 1979). This did not correspond with the findings of Meyer and Nelson (1978), Dellinger (1978) and Germane et al., (1989), who found a large variation in crown and root morphology, and this could lead to teeth not being moved into their ideal positions. It has also been shown that there was a direct relationship between the curvature of the bracket, adaptation of the bracket to the buccal surface of teeth and the resistance to the application of forces (Viana et al., 2005).

In fixed orthodontics only a few techniques exist in the literature to determine the buccal inclination of teeth and even fewer techniques to investigate the relation of the orthodontic bracket base curve to that of the buccal surface of the tooth.

Chapter 2

Review of Literature

2.1 Curvature of Teeth

Andrews (1979) recorded vestibular curvature of the tooth in the incisal-gingival direction by superimposing templets of circles onto dental plaster models. The models belonged to 120 Caucasian non-orthodontic patients with normal occlusion. Watanabe and Koga (2001) performed a morphometric study on the contours of teeth in a Japanese population and used a series of custom-made acrylic arcs whose radii ranged between 1 - 40 mm. The contour of the tooth was measured along the facial axis of the clinical crown and the facial axis reference plane. They found the largest variation in vertical crown contour in the maxilla to be that of the maxillary second premolar. The canine showed the greatest vertical contour in the mandible. The largest variation in the horizontal direction was that of the second molar in the maxilla and the lateral incisor in the mandible.

Dellinger (1978) stated that that in order to obtain the correct positioning of the bracket on the buccal surface of the tooth, the bracket base curvature should be very similar to the curvature of that of the tooth. This hypothesis was confirmed in a study by Miethke and Melsen (1999). The aforementioned authors investigated the effect of tooth morphology variation and bracket position on first and third order corrections with pre-adjusted appliances. They made use of plaster models which where sectioned to expose the bracket margin and digitized the teeth using photography. The curvature of the tooth was determined using the formula for a parabola. It was concluded that intraindividual variations in tooth morphology were larger than the variations between different types of preadjusted appliances. Hence if a straight-wire approach was followed, custom brackets should be used (Miethka and Melsen, 1999).

The importance of the tooth and bracket curvature originate from Germane et al., (1989), who postulated that the effective torque of a bracket is influenced by the difference in tooth morphology and the bracket base. They also found that the amount of effective torque acting on the tooth varied when the bracket was placed at different heights on the tooth (orthodontic prescription). Meyer and Nelson (1978) stated that a change of up to 15° in torque occurred when the bracket was bonded 3 mm from the prescribed position.

Linklater and Gordon (2001) identified a relationship between the differences in shear bond strength to the gross anatomical variability of the teeth in their sample. They reported that certain tooth types might have greater morphological variation than others, hence generating a variable adhesive film thickness and these factors altered bond strength characteristics.

2.2 Microleakage and Bond Failure

Decalcification of enamel i.e. white spot lesion (WSLs) remain a clinical issue that frequently become visible on orthodontic patients at de-banding. This is due to the fixed orthodontic attachments acting as a site for increased plaque retention (Gorelick et al., 1982). A meta-analysis by Venkatachalapathy et al., (2015) investigated the incidence and prevalence of WSLs in patients undergoing fixed orthodontic therapy. Of the 14 studies included in the analysis, the prevalence rate of WSLs was found to be 68.4% of 1242 patients. Julien et al., (2013) reported that WSLs were 2.5 times more frequent in the maxillary than in the mandibular arch. Boersma et al., (2004) found the prevalence of WSLs to be 97% in a sample of 64 patients who were de-banded. Most investigations have studied the WSLs around the brackets and not beneath the brackets. James et al., (2003) indicated an increased risk of microleakage beneath the orthodontic bracket, at the tooth resin material interface.

If the bracket adaptation is poor, a greater volume of resin material is required to fill the space between tooth and the bracket. Polymerization shrinkage of the resin material may lead to gap formation at the material enamel interface and in turn cause microleakage permitting passage of bacteria and oral fluids from the oral cavity. Microleakage can increase the likelihood of recurrent caries and post-operative sensitivity (St George, 2002). This was considered as supportive in the formation of WSLs on the enamel at the bracket-resin material interface (Uysal et al., 2008).

Additionally, the bracket material plays a role, since Arhun et al., (2006) found metal brackets contracted and expanded more than ceramic brackets, enamel, or the adhesive systems. This led to the production of micro-gaps between the bracket and the adhesive system and caused leaking of oral fluids and bacteria beneath the brackets. This caused more leakage at the resin material-bracket interface, which lead to a lower clinical sheer bond strength over time and WSLs formation. They also found microleakage scores at the gingival margin of the bracket to be greater than that of the incisal aspect. It was attributed the surface curvature anatomy of the tooth at the gingival aspect and the increased amount of adhesive required to fill the additional space (Arhun et al., 2006).

Vijyakumar et al., (2014) performed an *in vivo* study on the reason for orthodontic bond failures. The study contained a sample size of 30 patients over a six-month period. It assessed the difference in bond failure rates for direct and indirect bonding of brackets as well as for individual teeth. The results of the study illustrated that the maxillary second premolar to had one of the highest bond failure rates at 16.6%. The bond failure of maxillary premolar brackets where attributed to saliva seepage and variation in adhesive thickness. Additional reasons suggested were, aprismatic enamel and the increased curvature of buccal surface that may have affected the micro-mechanical bond strength of the brackets.

2.3 The Size of the Bracket Base

The average size of a metal orthodontic bracket was between 9 and 12 mm^2 (Bishara et al., 1999; Sorel et al., 2002). There has been a decrease of the orthodontic bases reported in 2003 of up to 75% (Matasa 2003). The size of the base play an important role in oral hygiene, bond strength and aesthetics (Matasa 2003). The metal bases rely on mechanical retention to the cement that is subsequently chemically bonded to the tooth structure due to an adhesive (Resin cements) or an ion exchange interface (Glass ionomer cements) for bond strength. Hudson et al., (2011) assessed three different bracket bases and its effect on sheer bond strength. The study concluded that size and design of the bracket bases influences the sheer bond strength (Hudson et al., 2011). Larger retentive bases improve the adhesion of the base. However, it does also increase the risk of fracture at the bracket adhesive interface (Cozza et al., 2006).

2.4 Curvature of Bracket

Gontijo et al., (2004) aimed to determine the average occluso-gingival and mesio-distal curvature of straight-wire brackets. Using the radius of the curve of the bracket bases, they found there to be a great variability in the measure between four different brands for the same bracket.

The orthodontic bracket is cemented on the buccal surface of the tooth with the appropriate cement. The closer the curvature of the base to that of the tooth, the closer adaptation it will assume. It will consequently have better adhesion, retention and distribute the forces on the tooth more efficiently in all dimensions (Gontijo et al., 2004).

The design of an orthodontic bracket has been identified as an item of importance. Bracket base adaptation, rotational position, vertical position and slot angulation are four key criteria required for successful placement of orthodontic brackets (Carlson and Johnson (2001). It was suggested that if the curvature of the bracket base does not follow the curvature of the tooth, then adjustments should be made to the bracket. These adjustments would include either increasing or flattening the concavity of the bracket base.

2.5 The Maxillary Second Premolar

According to Miethke and Melsen (1999) the maxillary premolars, after the mandibular and maxillary molars, are teeth which show a great amount of variation in its buccal morphology. Additionally, the largest variation in vertical crown contour was found to be that of the maxillary second premolar (Watanabe and Koga, 2001). In clinical practice, the maxillary first premolar is the tooth most often extracted during orthodontic treatment (Dardengo et al., 2016). The second maxillary premolar is therefore the more appropriate tooth to use for studies on premolars.

2.6 Micro-Computer Tomography Scanner

Computer-aided Design and Computer-aided Manufacturing (CAD/CAM) is a manufacturing process for designing and fabricating work pieces with the aid of computer software and computer-controlled equipment (Nassruddin, 2015). Digitisation of the item is produced by scanners followed by the CAD software serving as the platform where the creation, analysis, modification or optimization of engineering drawing or designs take place. The scanner creating the digital image/model of the item can be a contact scanner or an optical scanner. Both scanner types collect data from the surface of the item and convert it into three dimensional co-ordinates in order to present the CAD software with a three-dimensional model. The CAD software can also receive data from a radiographic source like a CT scanner, typically used for medical purposes. Industrial CT scanners are also available and can scan the item in the form of sliced of two-dimensional images which are reconstructed into a three-dimensional object by attaching the two-dimensional images into what is known as a bundle (Nassruddin, 2015). An example of this type of CT scanning is a Micro-Computer Tomography Scanner (Micro-CT), which produces a better spartial resolution and smaller voxel size than conventional industrial CT scanning and hence has greater accuracy (Swaine and Xue, 2009).

Micro-CT technology is rapidly becoming an essential component of many academic and industrial research laboratories due to the wide array of applications for direct examination and evaluation of products/specimens by Micro-CT imaging. Advanced investigations have been completed on mineralized tissue such tooth, bone and materials such as ceramics, polymers and biomaterial scaffolds (Swaine and Xue, 2009).

Micro-CT imaging has multiple uses in dental research. This includes studies in enamel thickness and tooth measurements where Micro-CT was shown to accurately depict variations in size and thickness (Olejniczak and Grine, 2006). The accuracy of Micro-CT imaging was also compared to measurements taking by direct measurement, 3D-scanners and by photography. The results indicated that Micro-CT was a reliable method and it was a useful device for measuring both internal and external tooth structures (Kim et al., 2007). Micro-CT imaging also made it possible to analyse important aspects of root canal morphology such as root canal curvatures (Jafarzadah and Wu, 2007) and the efficacy of root canal obturation (Bergmans et al., 2001). Other areas where Micro-CT imaging has been employed in dentistry include the study of craniofacial skeletal development, structure, biomechanics, tissue engineering, implant as well as peri-implant bone investigations (Swaine and Xue, 2009).

2.7 Motivation for the study

With the aforementioned factors in mind, this dissertation will use Micro-CT to investigate the relationship between the curvature of second maxillary premolar teeth and the bases of three different orthodontic bracket brands.

The importance of the study originates from the recommendation from Carlson and Johnson (2001) who determined that an ideal base contour would be one that had a uniform volume of adhesive at the bracket base-tooth interface during bracket seating. The limitation of this clinical recommendation was the variability of the clinicians achieving a consistently adapted bracket to the curvature of the tooth. The study provide insight to the manufacturers that will allow the manufacturer to design bracket bases with a suitable adaptation to a wide variety of curvatures.

The hypothesis of the study was therefore, that there would be a significant difference between the curvatures of the randomly selected sample of pre-molars in relation to the curvatures of the bracket bases of the three brands.

Chapter 3

Materials and Methods

3.1 Aims and objectives

The aim of the study was to compare the buccal curvatures of the maxillary second premolars with the curvatures of three orthodontic bracket brands using a Micro-CT scanner.

The objectives of the study were to :

- Calculate the central angle of the maxillary second premolar in the first quadrant at the area of the mesial bracket margin and the gingival bracket margin for the 4 mm, 3 mm and combined prescriptions.
- Assess the variations in the central angle of the maxillary second premolar in the first quadrant at the mesial bracket margin and gingival bracket margin for 4 mm, 3 mm and combined prescriptions.
- Calculate the central angle of the fitting surface of each bracket system at the mesial bracket margin and the gingival bracket margin.
- Compare the mean angular difference of the central angle of the teeth versus the corresponding bracket fitting surface.

3.2 Study Design

The study was a comparative study using randomly selected maxillary diagnostic models from the archives of the Department of Orthodontics and three brands of orthodontic brackets fitted to these randomly selected premolar teeth.

3.3 Ethical Considerations

Approval to conduct the study was received from the University of the Western Cape Research Ethics Committee (Project Registration Number: BM19/1/10).

3.4 Study Sample

The study sample included 33 archived and anonymised orthodontic plaster models. These models were selected at random from the archives of the Department of Orthodontics; University of the Western Cape. Only the maxillary second premolar was of interest in this study. Before trimming the plaster models, the mesial and distal contact points were marked with a pencil and the models were trimmed to this point to prevent over trimming of the teeth. Teeth with both, short and normal crown heights were included in the study to simulate clinically relevant situations. The sample contained 19 teeth at 4 mm prescription and 14 teeth at 3 mm prescription. Numbers were etched into the plaster of each tooth for identification purposes. In order to establish a repeatable method, each maxillary second premolar was separated from the models and placed on a cylindrical sample carrier.

The corresponding orthodontic bracket from three different manufacturers were included for the maxillary second premolar in the first quadrant:

- Bioquick (Forestadent)
- Innovation (GAC)
- Victory series (3M Unitek)

3.5 Micro-CT Image acquisition

3.5.1 Image acquisition of the orthodontic brackets

1. The orthodontic brackets were mounted together using periphery wax on a cylindrical sample carrier. (Figure 1 and Figure 2)
2. The mounted orthodontic brackets are placed in the X-ray micro-computer tomography scanner, Nikon Metrology XTH 225 ST X-ray micro-computer tomography scanner (Yokohama, Japan) (Figure 3 and Figure 4).

3. X-ray micro-computer tomography scan were taken at 100kV with a beam current of 200μA and an exposure of 1fps.

4. The scan data were transferred to the software analysis program (Volume graphics VG Studio max 3.2.5).

5. The orthodontic brackets were separated and analysed individually in the software.

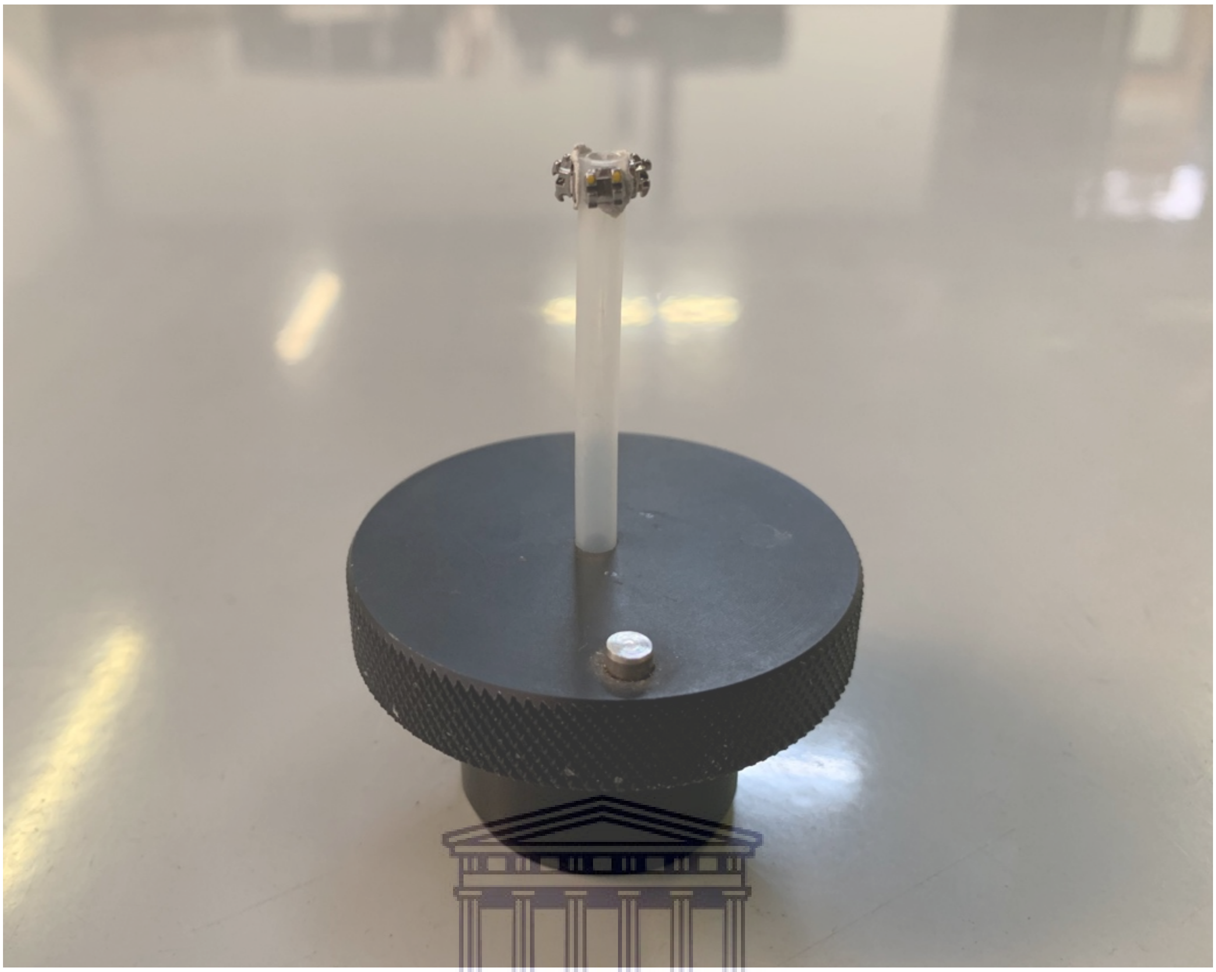

Figure 1: Side view of mounted orthodontic brackets

Figure 2: Superior view of mounted brackets

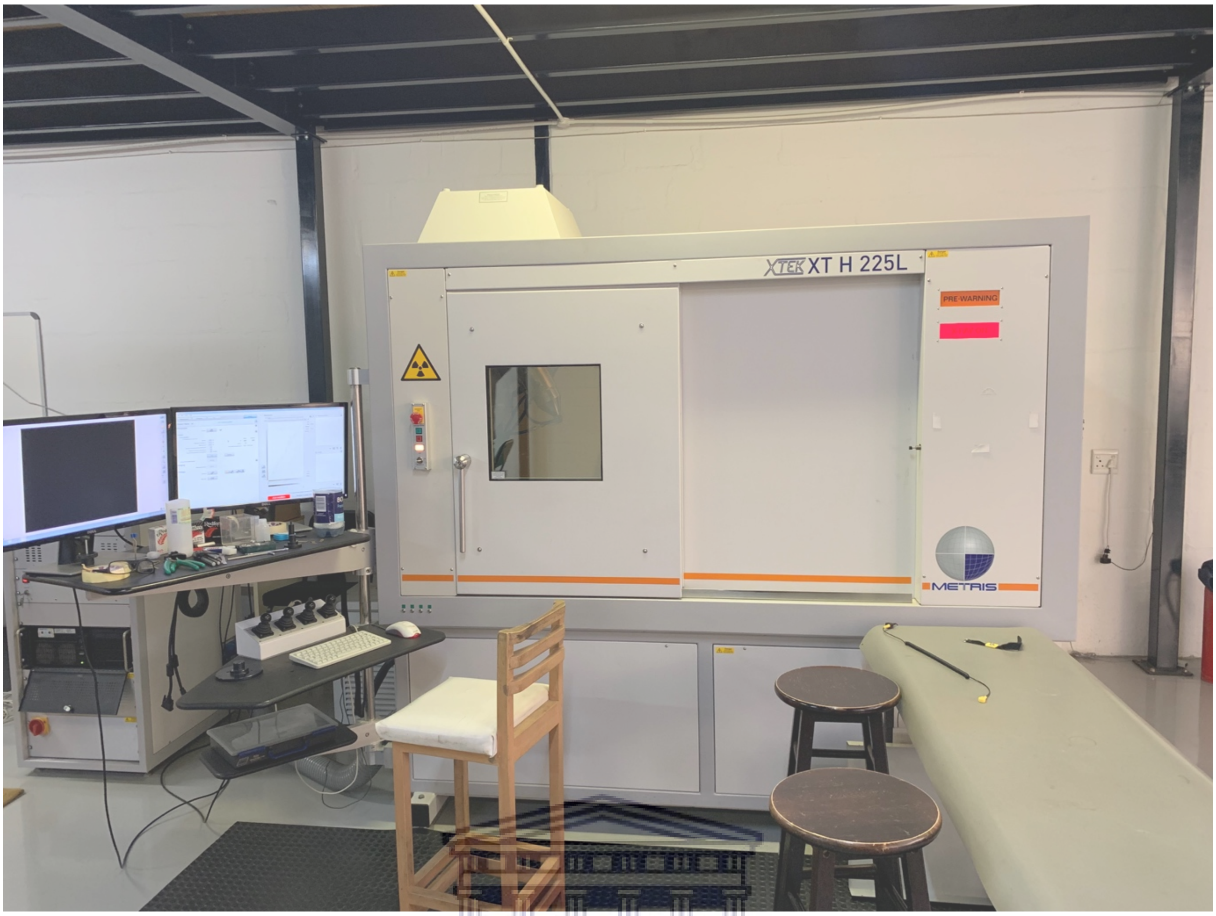

Figure 3: Nikon Metrology XTH 225 ST X-ray micro-computer tomography scanner

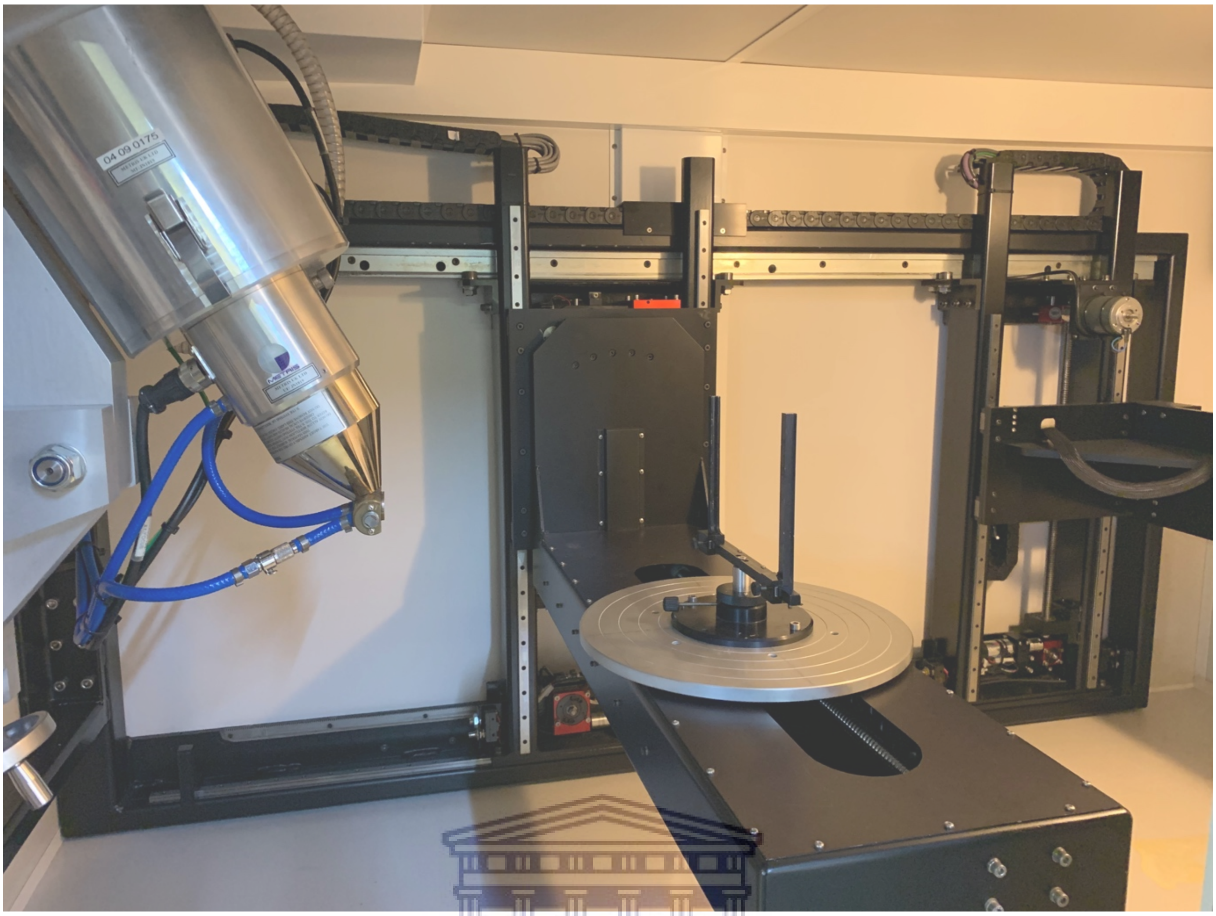

Figure 4: Internal chamber of Micro-CT Scanner

3.5.2 Image acquisition of the teeth

1. Each tooth is inscribed with a number for identification purposes, since there are models randomly selected to allow a varied sample of maxillary second premolar teeth.

2. The teeth were mounted on a firm foam holder in batches of three and scanned in the X-ray micro-computer tomography scanner (Figure 3).

3. X-ray micro-computer tomography scan was taken at 100kV with a beam current of 200μA and an exposure of 1fps.

4. The scan data was transferred to the software analysis program (Volume graphics VG Studio max 3.2.5).

5. The teeth were separated and analysed individually in the software.

Figure 5: Plaster teeth mounted in Styrofoam

3.6 Measurement parameters of Orthodontic brackets

3.6.1 Height-width determination of orthodontic brackets

1. The height and width of each bracket was measured in the analysis software and recorded.

2. The height-width of the three orthodontic brackets were: Bioquick (Forestadent) 3.07 mm height/3.45 mm width; Innovation (GAC) 3.25/4.46 mm and Victory series (3M Unitek) 2.88/3.29 mm.

3.6.2 Standardized orthodontic bracket contact area

Orthodontic brackets from different companies have varied designs with regard to shape and edges of the orthodontic brackets. In order to standardize the adaptation calculation of orthodontic brackets to teeth a standardized 75% of the orthodontic brackets' height-width was calculated known as the "Standardized area of contact".

The Standardized area of contact represented by 75% of the height and width measurements are calculated as follows:

- Height from target point of orthodontic bracket = 0.75 (height of orthodontic bracket / 2)
- Width from target point of orthodontic bracket = 0.75 (width of orthodontic bracket / 2)

The Standardized area of contact represented by 75% of the height and width measurements are calculated for the three orthodontic brackets as represented in Table 1.

Table 1: Standardized area for the three orthodontic brackets

Bracket	**Height**	**Width**
Bioquick (Forestadent)	1.15 mm (Vertical offset bracket: Bioquick)	1.30 mm (Horizontal offset bracket: Bioquick)
Innovation (GAC)	1.21 mm (Vertical offset bracket: Innovation)	1.30 mm (Horizontal offset bracket: Innovation)
Victory series (3M Unitek)	1.08 mm (Vertical offset bracket: Victory series)	1.23 mm (Horizontal offset bracket: Victory series)

3.6.3 Co-ordinate and target point determination

1. The centre point of the orthodontic brackets is known as the “target point”.
2. The centre point of the orthodontic brackets were calculated, and a co-ordinate assigned to the centre point.
3. The centre of the orthodontic bracket is determined by using the height and width (Figure 2).

4. Height from target point of orthodontic bracket = 0.75 (height of orthodontic bracket / 2).
5. Width from target point of orthodontic bracket = 0.75 (width of orthodontic bracket / 2).
6. The standardized area of contact represented by 75% of the height and width measurements were calculated for the three orthodontic brackets as represented in Table 1.
7. The x and y - coordinates of the target point on the tooth is recorded, the z - coordinates are not required and therefore excluded.
8. Using the co-ordinates of the target point as the main reference point, the co-ordinates for three additional landmarks can be determined: Point A as the "occlusal mesial margin"; Point B as the "gingival mesial margin" and Point C as the "gingival distal margin" on the orthodontic bracket (Figure 2).
9. The x and y coordinates of the target point on the tooth is recorded. Table 2 identifies the co-ordinate calculation of the three additional landmarks (Points A, B and C) for the Victory series bracket.

Table 2: Co-ordinate calculation of the three additional landmarks for the Victory series bracket.

Point	**Co-ordinate determination for Victory series bracket**
Point A as the Occlusal mesial margin	• X coordinate Victory series bracket= X of target +1.23 mm (Horizontal offset Victory series bracket) • Y coordinate of Bracket A = Y of target -1.08 mm (Vertical offset Victory series bracket) (Figure 7).
Point B as the Gingival mesial margin	• X coordinate Victory series bracket = X of target +1.23 mm (Horizontal offset Bracket A)

	• Y coordinate of Bracket A = Y of target +1.08 mm (Vertical offset Victory series bracket) (Figure 7).
Point C as the Gingival distal margin	• X coordinate Victory series bracket = X of target -1.23 mm (Horizontal offset Bracket A) • Y coordinate of Victory series bracket = Y of target +1.08 mm (Vertical offset Victory series bracket) (Figure 8).

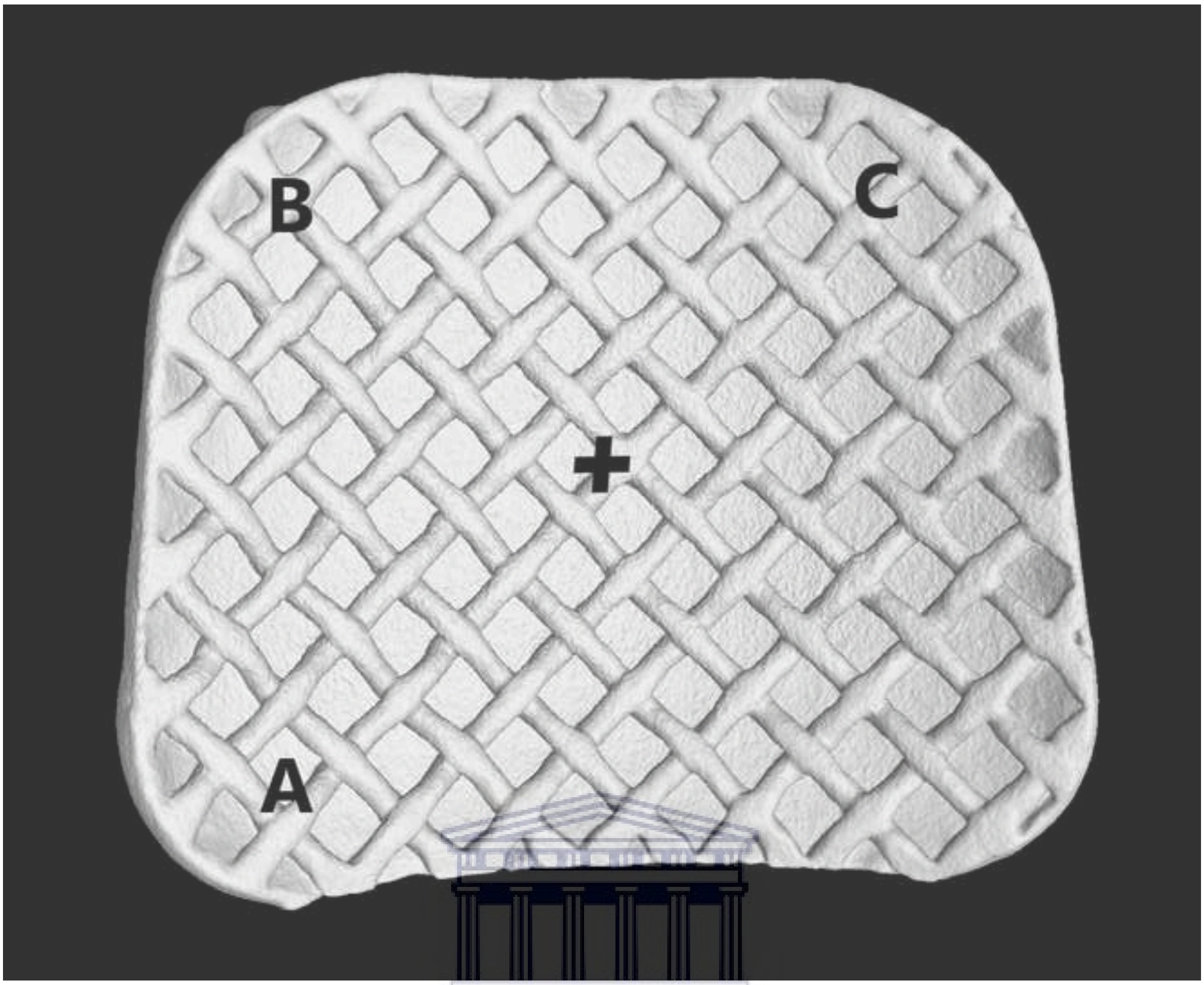

Figure 6: Target Point, Point A, Point B and Point C on the bracket

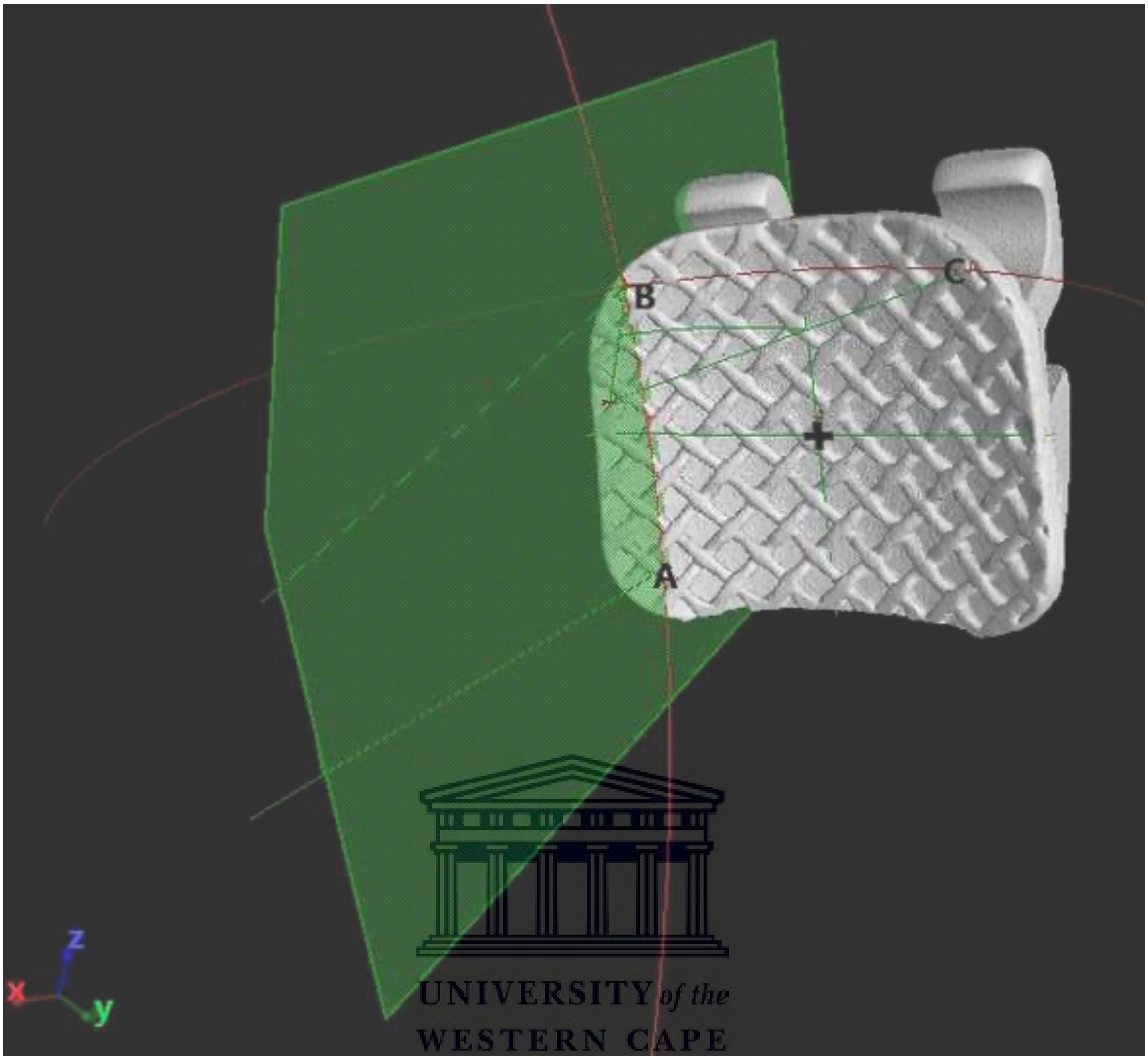

Figure 7: Point A as the Occlusal mesial margin and Point B as the Ginigival mesial margin

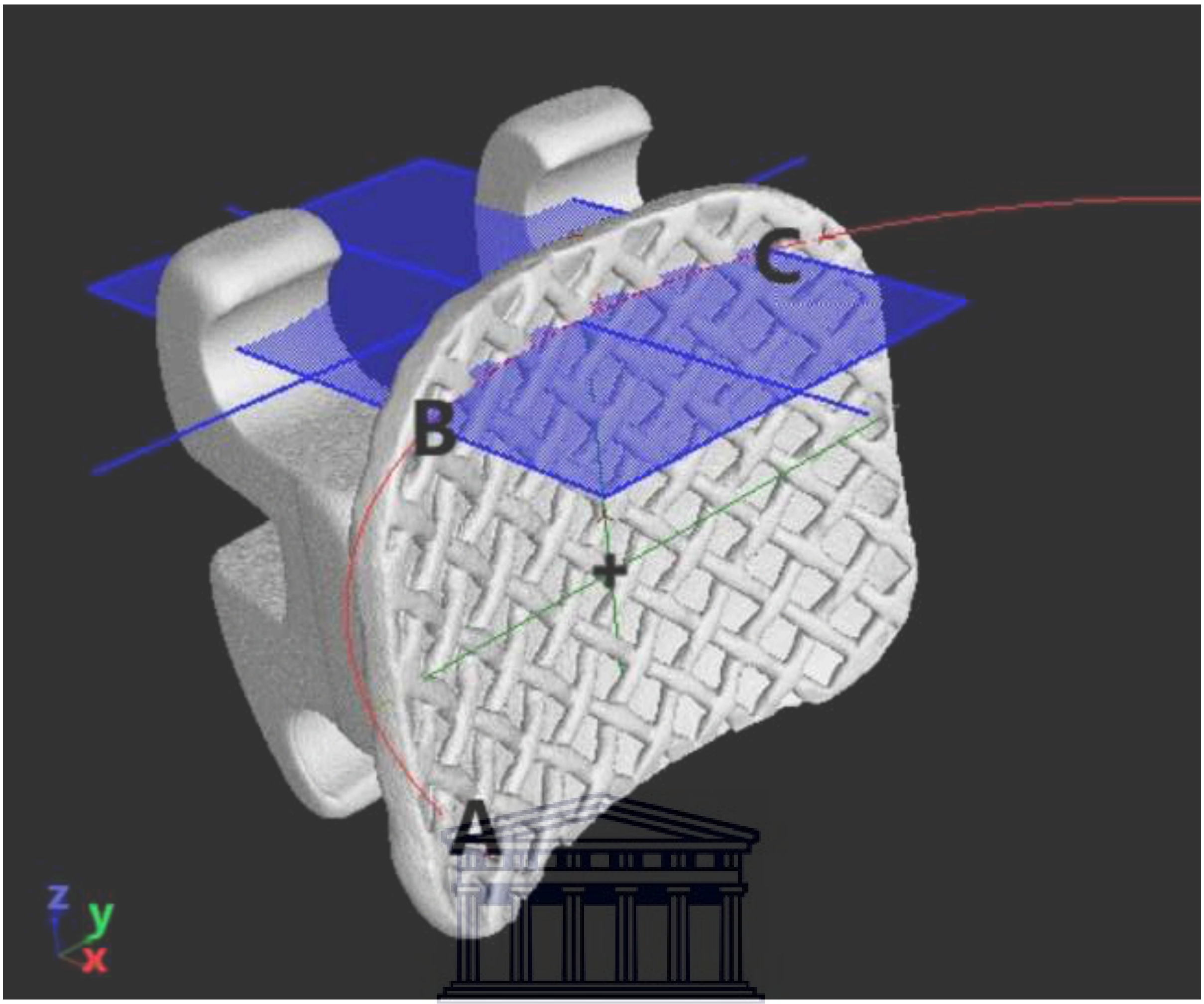

Figure 8: Point B as mesial gingival margin and Point C as distal gingival margin

3.6.4 Orthodontic bracket curvature Determination

In order to assess the curvature of the orthodontic bracket and how it relates to the contact surface on the tooth surface, the curvature was assessed with the closest fitting circle, followed by the determination of the angle. The angle was formed between the centre point of the best fitting circle and the landmarks of Points B-A (Figure 7) and Points B-C (Figure 8).

3.6.5 Determining the curvature of the orthodontic bracket surface:

1. The Mesial curve ran between Point B and Point A (Figure 7) and the gingival curve ran from Point B to Point C (Figure 8)

2. The length of the curve was measured for both the mesial and gingival curve using the measuring tool on VG Studio max 3.2.5 (Hiedelberg, Germany 2018) and the

midpoint of each curve is determined i.e. Midpoint of Curve (represented by "+" on Figures 9, 10).

3. For the Mesial curve, an additional point was placed midway between the "Midpoint of the curve" and Point A and midway between the Midpoint of the curve and Point B (Figure 9).

4. For the gingival curve, an additional point was placed midway between the "Midpoint of the curve" and Point B and midway between the Midpoint of the curve and Point C (Figure 10).

5. A total of 5 Points were now present on each curve to allow for standardisation in fitting of the best fitting circle.

6. The best fitting circle (Du Plessis et al., 2017) was fitted to the curve which passes through these 5 points on the curve using the circle tool in VG Studio max 3.2.5 (Hiedelberg, Germany 2018) (Figures 9, 10).

7. The origin of the circle was marked and two radii are constructed using line segments starting at the origin and terminating at Point A and Point B for the mesial curve and Point B and Point C for the gingival curve (Figures 9, 10).

8. The angle between radii of the mesial curve was measured in degrees (Figure 9).

9. The angle between the radii of the gingival curve was measured in degrees (Figure 10).

10. The angular and radii measurements was then recorded on an Excel spreadsheet for the mesial curve and the gingival curve.

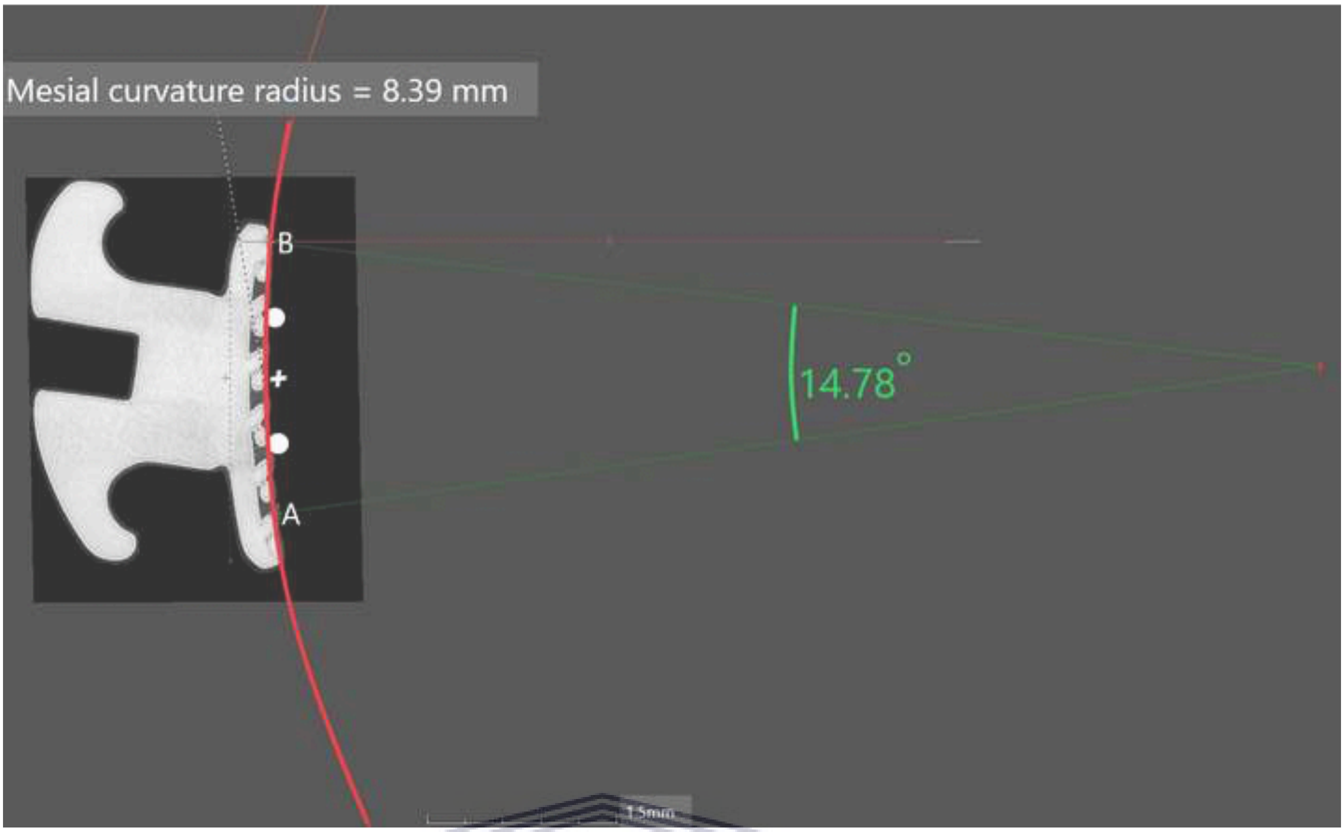

Figure 9: Vertical slice of the bracket illustrating the points placed to determine the mesial curve. The origin of the circle, the radii and the angle are also illustrated.

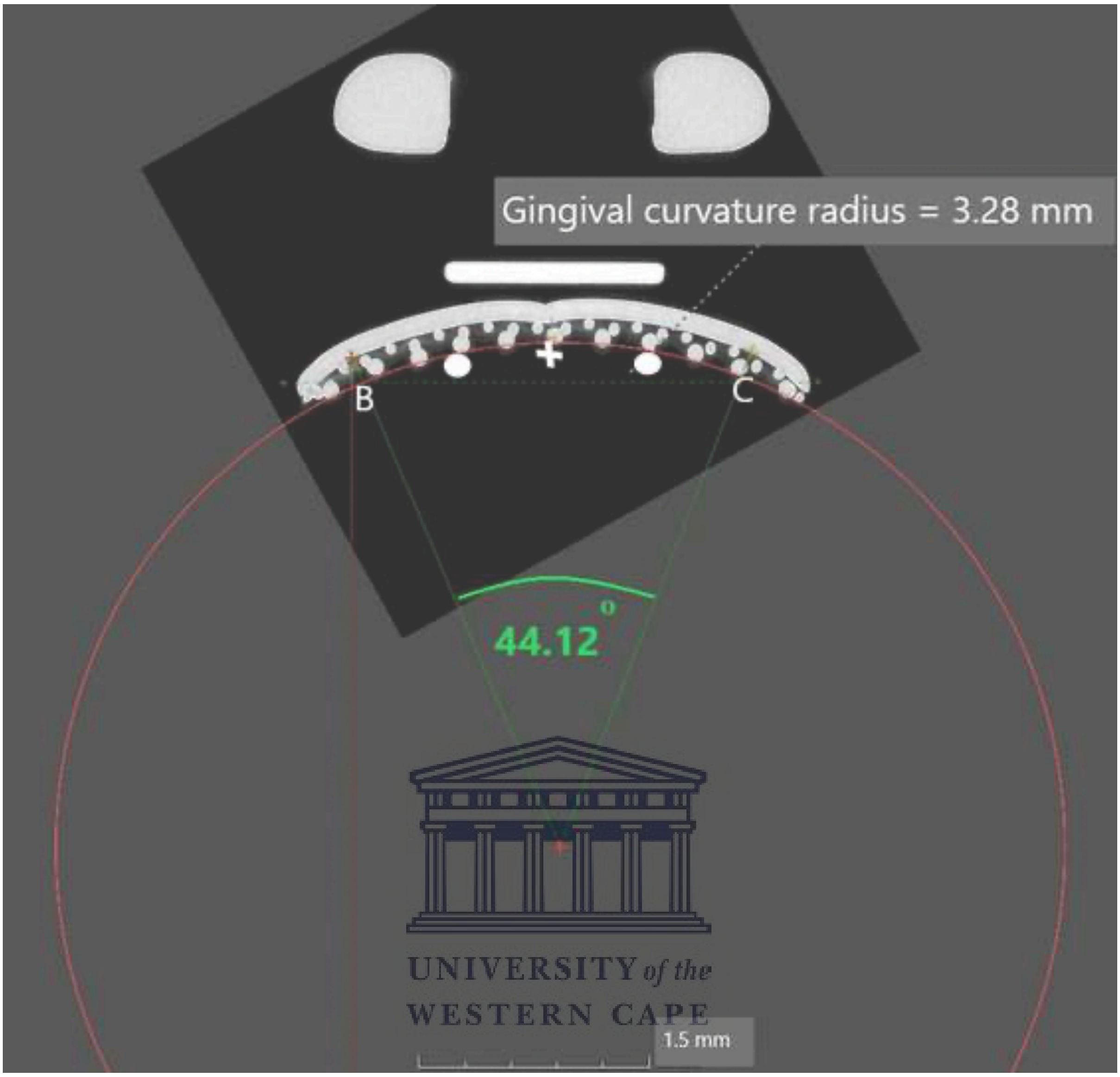

Figure 10: Horizontal slice of the bracket illustrating the points on the gingival curve. The origin of the circle, the radii and the angle are also illustrated.

3.7 Measurement parameters of teeth

Height-width determination of teeth

1. Once the tooth was digitised, the width of the tooth was measured from contact point to contact point.

2. The measured width and cusp tip was used to determine the central axis of the tooth (Figure 11).

3. The assessed orthodontic brackets have a prescription of 4 mm and therefore the “target point was placed on the central axis line 4 mm from the cusp tip (Figure 11). For shorter clinical crowns a height of 3 mm was used.

4. The x, y and z coordinates of the target point on the tooth was recorded as per the reading of the analysis software. The coordinates of the target point for each tooth varied however the offsets remained the same regardless of being 3 mm of 4 mm.

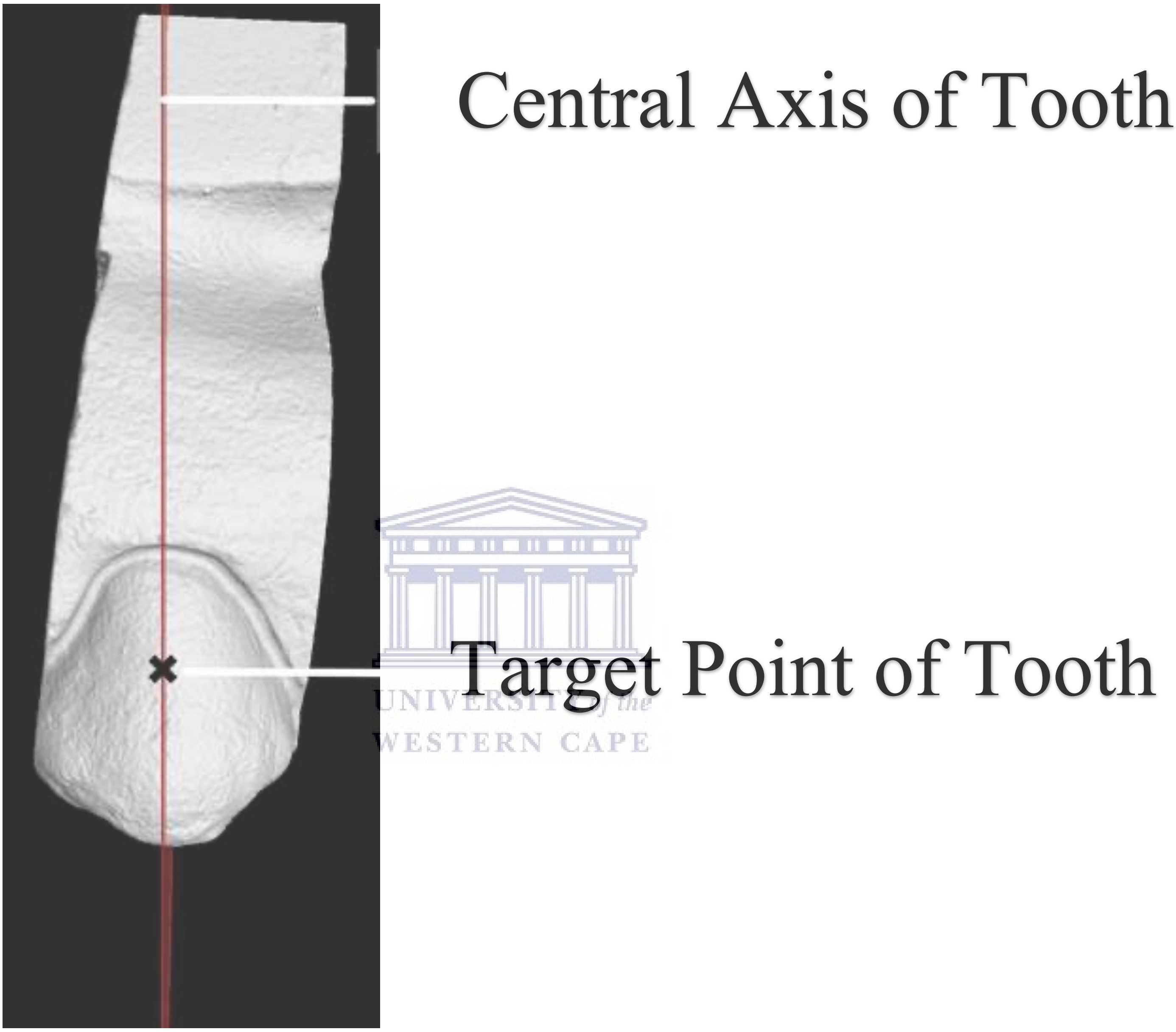

Figure 11: Facial view of the tooth illustrating the central axis and the target point

3.8 Orthodontic bracket placement on teeth

The co-ordinate points were determined for the orthodontic brackets in relation to the 4 mm and 3 mm orthodontic bracket prescriptions and represented in Table 3 for the first tooth as per Figure 11. These co-ordinate points were plotted on the tooth and created two curvatures for each bracket to represent the "Standardized area of contact" which is the 75% contact area of the bracket on the tooth.

Table 3: Co-ordinates on a tooth for each bracket

Tooth number 1	X	Y	Z
Target area on tooth located at	0.63	-5.7	-2.87
Bioquick point A	1.92	-5.29	-4.02
Bioquick point B	1.92	-5.06	-1.72
Bioquick point C	-0.66	-5.63	-1.72
Innovation point A	1.93	-5.27	-4.09
Innovation point B	1.93	-5.14	-1.65
Innovation point C	-0,67	-5.61	-1.65
Victory series point A	1.86	-5.33	-3.95
Victory series point B	1.86	-5.11	-1.79

Victory series point C	-0.60	-5.68	-1.79

For the Bracket Victory series, the mesial curve was determined from Point B to Point A and the gingival curve from Point A to Point C.

3.9 Curve determination of the teeth

The images of the teeth were sliced at these co-ordinate points, exposing their curvatures. The co-ordinate points from the orthodontic brackets were then placed on the mesial curve of the sliced tooth:

1. The first three co-ordinate points (x, y, z) were e.g. For Point A and Point B for the Victory series bracket.
2. The length of the curve was measured for both the Mesial and Gingival curve using the measuring tool on VG Studio max 3.2.5 (Hiedelberg, Germany 2018) and the midpoint of each curve is determined i.e. Midpoint of Curve.

3. An additional point was placed midway between Point A and the Midpoint of the curve.
4. An additional point was placed midway between Point B and the Midpoint of the curve (Figure 8).

5. A circle was then fitted over these points using the circle tool within the VG Studio max 3.2.5 (Hiedelberg, Germany 2018) program, which most closely fitted the arc. The origin of the circle was automatically placed by the VG Studio max 3.2.5 (Hiedelberg, Germany 2018). A radius was extended from the origin of the circle to Point A and another radius was extended from the origin to Point B. The angle between the radii was recorded as the central angle (Figure 8).

The same process is repeated for the gingival curve providing the following points placed on it:

- The first points were Point B and Point C

- The arc length was measured, and point was placed at the midpoint of the curve.
- A point was place midway between Point B and the midpoint of the curve.
- A point was place midway between Point C and the midpoint of the curve.

A circle is then fitted over these points using the circle tool within the VG Studio max 3.2.5 (Hiedelberg, Germany 2018) program, which most closely fitted the arc. The origin of the circle was automatically placed by the VG Studio max 3.2.5 (Hiedelberg, Germany 2018). A radius was extended from the origin of the circle to point B and another radius was extended from the origin to point C. The angle between the radii of point B and point C is then recorded as the central angle (Figure 13).

7. The process was then repeated for each of the orthodontic bracket coordinates on each tooth result in a:

- mesial and gingival angle measurement for the Bioquick (Forestadent) bracket.
- mesial angle and gingival angle measurement for the Innovation (GAC) bracket.
- mesial and gingival angle measurement for the Victory series (3M Unitek) bracket.

8. These values were transferred to excel spreadsheet. The angles of the three brackets are then compared to the angles of the curvatures on the tooth of each brand to determine which bracket has a curvature which is closest to the teeth.

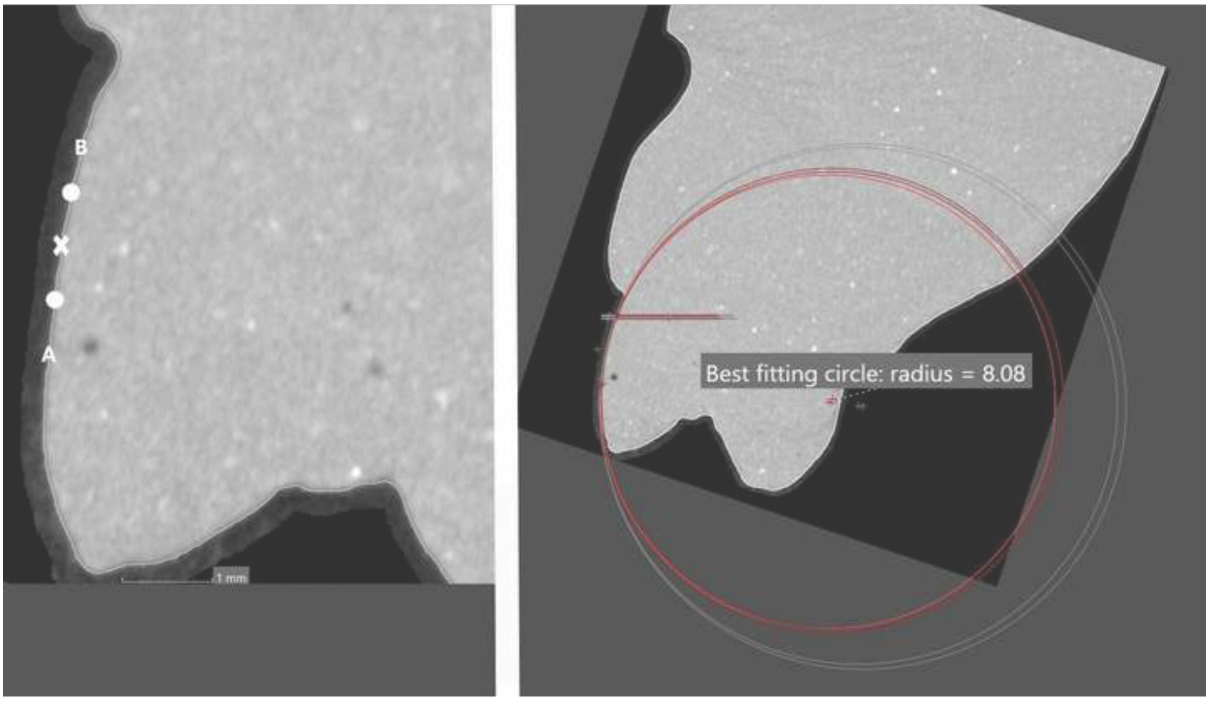

Figure 12: The vertical slice at the mesial margin illustrates the points required to determine the mesial curve. The closest fitting circle, the origin, the radii and the angel are demonstrated.

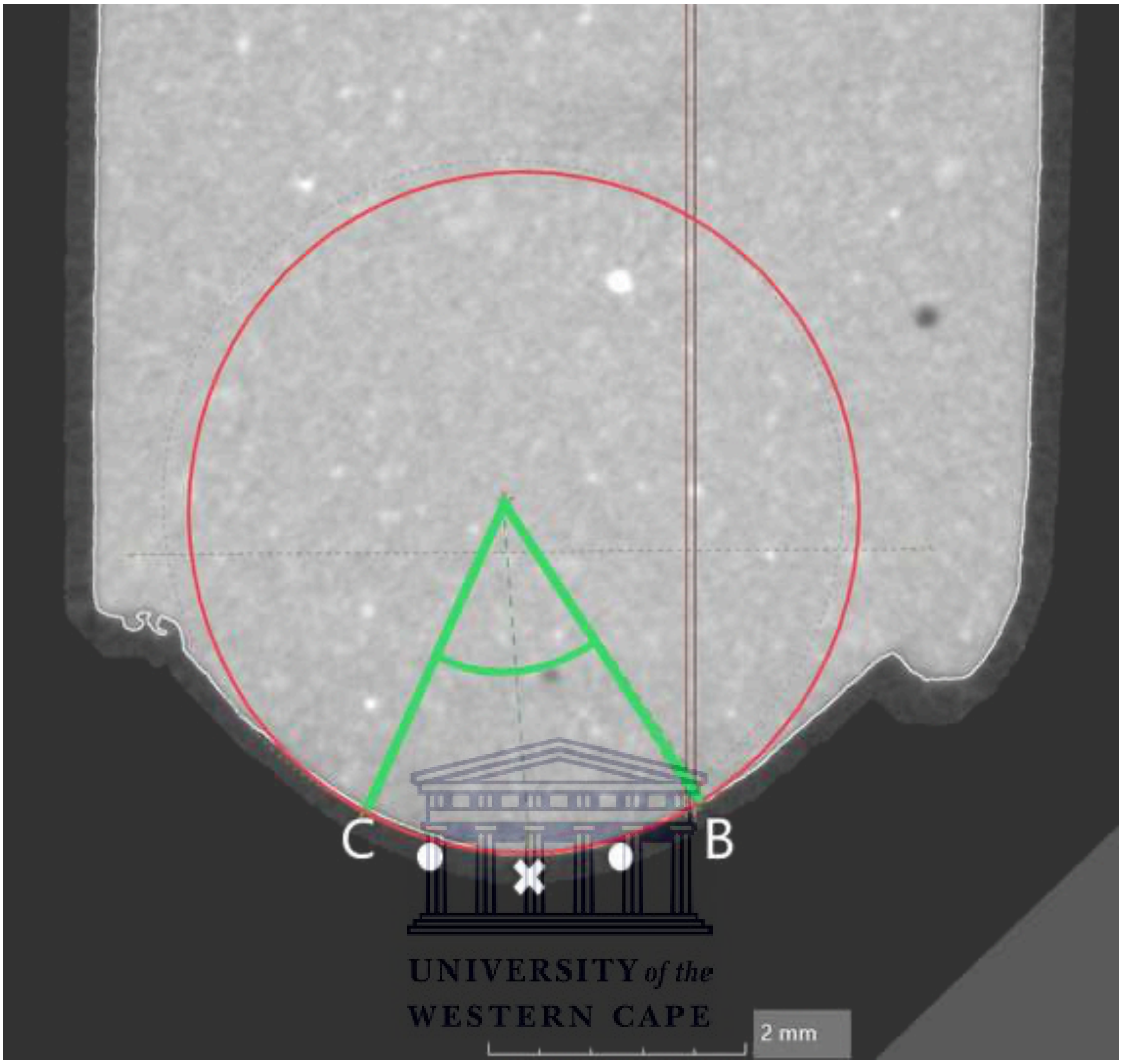

Figure 13: A horizontal slice that illustrates the points required to determine the gingival curve. Also show are the closest fitting circle, the radii, the angle, and the origin.

3.10 Statistical analysis

3.10.1 Background

Analysis of variance was completed by ANOVA, a statistical technique that is used to check if the means of two of more groups are significantly different from one another. It considers the impact of one or more factors by comparing the mean values of different samples. A one-way ANOVA compares the variances within the group means with only one independent variable or factor. A two-way ANOVA instead compares multiple groups of factors and is designed to assess the inter-relationship of two variables on the dependent variable.

3.10.2 Validity and Reliability

For the analysis 20% of the sample was re-examined by an experienced Micro-CT operator and the primary investigator (Fakir). The analysis included both the angle determination on the tooth and that of the brackets in order to assess the intra-observer reliability. The operator was blinded to the previous results of the preceding month. Calibration of the operator was done by the primary investigator and a senior Micro-CT technician under the supervision of the project supervisor (Mulder).

The results were treated using a Pearson Correlation Coefficient to test the linear relationship between two variables. A r-value of -1 indicates a negative relation between the two variables. A r-value of 0 indicates there is no relation between the variables and a r-value of +1 indicates a strong relationship between the variables.

3.10.2 Analysis of the tooth angles

A one-way ANOVA was used for the analysis of the results to determine if there was a statistically significant difference in the angle values obtained from the teeth. The data for the tooth angles were shown as a mean (±Standard Deviation).

3.10.3 Analysis of the bracket type and tooth angle position

The angular measurements of each bracket were subtracted from the angular measurement for the corresponding curvature on the tooth. This created an “Angular Difference” between the bracket and the tooth. These values were then evaluated separately for teeth of the 4 mm script and the 3 mm script. The values were combined and evaluated together i.e. Joint scripts. (Should I call it the combined 4 and 3 mm?)

A two-way ANOVA was conducted to examine the effects of the bracket type and angle position on the difference from the tooth for the joint scripts. The data was shown as a mean (±Standard Deviation) and all assumptions for a two-way balanced ANOVA was met.

Pairwise comparisons are methods for analysing multiple population means in pairs to determine whether they are significantly different from one another. The Bonferroni method was chosen due to it being a simple method that allows many comparison statements to be made while still assuring an overall confidence coefficient is maintained (https://www.itl.nist.gov/div898/handbook/prc/section4/prc473.htm).

All pairwise comparisons were run for each sample main effect with reported 95% confidence intervals and p-values Bonferroni-adjusted within each sample main effect. All p-values are deemed statistically significant at $p < 0.05$.
The statistical analysis of the data was assessed using StataCorp 2017. Stata Statistical Software: Release 15. College Station, Tx : StataCorp LLC.

Chapter 4

Results

4.1 Validity and Reliability:

The inter examiner reliability testing was not possible due to the nature of the co-ordinate accuracy of the system – the method has been designed in a structured manner that the results are completely identical. The intra-examiner reliability was 0.987782, 95% CI [0.95560 to 0.996678] for brackets and 0.999642, 95% CI [0.982138 to 0.999993]. The results of the Pearson correlation coefficient of 0.987782 for the angles on the tooth and 0.999642 for the bracket angles indicate excellent reliability.

4.2 Sample Evaluation:

Script	Number of Teeth
4 mm	19
3 mm	14

4.3 Bracket Angle Estimates

Table 4: Data collected showing the values for the Bracket Angles in degrees.

Bracket	Victory Series	Innovation	Bioquick
Mesial Angle(°)	14.78	13.90	11.12
Gingival Angle(°)	48.70	44.12	61.12

The bracket angle estimate is a measurement of the curvature of the brackets at the pre-determined points (Figure 7 and 8). The mesial angles were smaller compared to the gingival angles where Innovation had the largest mesial angle, 13.90 compared to Bioquick, 11.12. Amongst the gingival angles Bioquick showed the largest angle, 61.12 compared to Innovation, 44.12 degrees.

4.4 Tooth Angulation values

Table 5:The mean curvature angles for the tooth prior to comparison.

Angle	Mean (±SD)
Mesial Angle	18.103 (±7.462)
Gingival Angle	56.383 (±10.672)

The mean curvature angles are taking from the three measured angles on the tooth for both the mesial and gingival areas. The standard variation of the means displays the variation in curvature of a premolar in a horizontal and vertical plane.

A one-way ANOVA was run to determine if there was a statistically significant difference readings between the different angles. There was a statistically significant difference between the readings of the gingival and mesial angles, $F(3, 92) = 1218.92$, $p < 0.001$.

4.5 Results for Joint Scripts (3 mm and 4 mm)

Table 6:Statistical Information for the Joint Scripts on the angular difference of the brackets at the mesial and gingival margin.

	Angular Difference (°)	
Bracket	**Mesial Angle mean (±SD)**	**Gingival Angle mean (±SD)**
Bioquick	-6.769 (±6.844)	5.836 (±13.580)
Innovation	-6.118 (±9.045)	-14.975 (±9.227)
Victory Series	-1.623 (±5.920)	-6.072 (±8.229)

Table 6 shows the mean angular differences for the three bracket brands at the mesial and gingival angle for the joint scripts. The small difference is at the mesial of the Victory series bracket -1.623 (±5.920). The largest difference for the mesial angle was that of Bioquick which was -6.769 (±6.844). The smallest angular difference at the gingival angle was Bioquick 5.836 (±13.580). The largest difference belonged to Innovation which was -14.975 (±9.227).

Table 7:The mean difference and standard deviation in angulation from tooth scores for brackets for the joint scripts.

Bracket	Mean (±SD)
Bioquick	0.446 (±9.252)
Innovation	-4.949 (±9.215)
Victory Series	-2.154 (±5.930)

Table 7 describes the mean combined angular difference of the combined mesial and gingival angle for each bracket brand. Here Bioquick shows the smallest overall angular difference at 0.446 (±9.252) and the largest overall angular difference is displayed by Innovation at -4.949 (±9.215).

Table 8:The mean differences for the combined brackets for the joint scripts at the mesial and gingival angle.

Angle(°)	Mean(±SD)
Mesial Angle	-4.837 (±7.664)
Gingival Angel	-0.076 (±1.066)

The combined angular differences for the joint scripts were less at the gingival angle -0.076 (±1.066) than at the mesial angle were the value was -4.837 (±7.664).

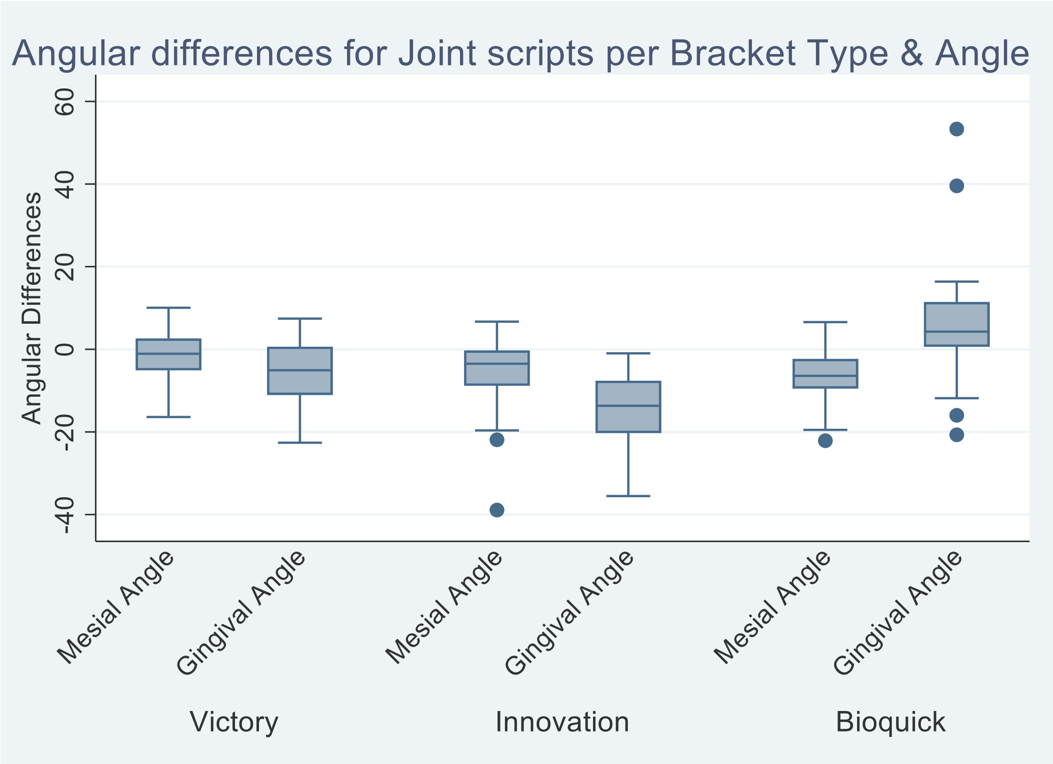

Figure 14 :Box plot of the joint scripts showing the angular differences at for the difference angles on the tooth for each bracket. The outliers were shown as a blue dots and have been included.

Each box represents (the interquartile area) the angular differences for each bracket, at either the mesial or gingival angle. The outliers were displayed as blue dots and the medians of each group of readings are displayed by the blue line. The gingival angle of Bioquick had the greatest number of outliers 4, as compared to two outliers for the mesial angle of the Innovation and one for the mesial angle of the Bioquick. Gingival angles where higher range than the mesial angles. The box illustrating the smallest range of differences was the mesial of the Victory series. The box illustrating the greatest range of differences was the gingival of Innovation. For the medians of the mesial differences, Victory series was closest to zero followed by Innovation and finally Bioquick. The median for Bioquick at the gingival angle was closest to zero as compared to that of Innovation and Victory at the gingival angle. The median of Innovation at the gingival angle was the greatest from zero.

The results of the two-way ANOVA showed a statistically significant interaction between bracket type and angle position on the difference in angulation from the tooth, F (6, 384) = 46.63, p < 0.001, partial η2 = 0.25. Therefore, an analysis of simple main effects for bracket type was performed with statistical significance receiving a Bonferroni adjustment and being accepted at the p < 0.025 level. There was a statistically significant difference in the mean angular difference of the teeth for different brackets, F (2, 384) = 20.61, p < 0.0001, partial η2 = 0.097, as for different angle position, F (3, 384) = 21.47, p < 0.0001, partial η2 = 0.144.

All pairwise comparisons were run for each simple main effect with reported 95% confidence intervals and p-values Bonferroni-adjusted within each simple main effect. Mean Difference in angulation from tooth scores for Victory was -2.15 (± 5.93), -4.94 (±9.22) and 0.45 (±9.26), respectively. Mean difference in angulation from tooth scores for the mesial angle and gingival angle were -4.84 (±7.66) and -5.07 (±13.55).

4.5.1 Mesial Angle

The angular difference between the bracket and tooth for Victory Series at the mesial angle was -1.624 (±5.920) and the angular difference for Innovation was -6.1184 (±9.0459). The pairwise comparison was done between the mesial angles. The angular difference between Innovation and Victory Series was -4.494 (SE±1.681), p = 0.517. Which did not show a statistically significant difference.

The angular difference between the bracket and tooth at the mesial margin for Victory Series was -1.624 (±5.920) and the angular difference for Bioquick -6.769 (±6.844). The pairwise comparison between the mesial angles of these to brackets was -5.145 (SE±1.681), p =0.156. Which did not show a statistically significant difference.

The angular difference between the bracket and the tooth for Bioquick at the mesial margin angle was -6.769 (±6.844) and the angular difference for Innovation was -6.1184 (±9.0459). The pairwise comparison was performed between the mesial angles of the two brackets and the difference between Innovation and Bioquick was -0.650 (SE±1.681), p = 1. Which did not show a statistically significant difference.

4.5.2 Gingival Angle

The angular difference between the bracket and the tooth for Victory Series at the gingival margin was -6.072 (± 8.229) and the angular difference for Innovation at the gingival angle was -14.975 (± 9.227). The pairwise comparison between the Victory Series and Innovation brackets at the gingival margin angle showed an angular difference of -8.903 (SE±1.681), p = 0. Which showed a statistically significant difference.

The angular difference between the bracket and the tooth for Victory Series at the gingival margin was -6.072 (± 8.229) and the angular difference for Bioquick at the gingival angle was 5.836 (± 13.580). The pairwise comparison between the Victory Series and Bioquick brackets at the gingival margin angle showed an angular difference of 11.908 (SE±1.681), p = 0. Which showed a statistically significant difference.

The angular difference between the bracket and the tooth for Innovation at the gingival margin was -14.975 (±9.227) and the angular difference for Bioquick at the gingival angle was 5.836 (±13.580). The pairwise comparison between the Innovation and Bioquick brackets at the gingival margin angle showed an angular difference of 20.811 (SE±1.681), p = 0. This indicated a significant difference between the two bracket types.

4.6 Results for the 4 mm Script

Table 9: Statistical information for the 4 mm on the angular difference of the brackets at the mesial and gingival margin.

	Angular Difference(°)	
Bracket	**Mesial Angle mean (±SD)**	**Gingival Angle mean (±SD)**
Bioquick	-7.358 (±8.002)	5.417 (±16.830)
Innovation	-7.579 (±10.858)	-17.850 (±9.000)
Victory Series	-2.037 (±6.783)	-8.649(±7.810)

Table 9 shows the mean angular differences for the three bracket brands at the mesial and gingival angle for the 4 mm script. The smallest difference is at the mesial of the Victory series bracket -2.037 (±6.783). The largest difference for the mesial angle was that of Innovation which was -7.579 (±10.858). The smallest angular difference at the gingival angle was Bioquick at 5.417 (1±6.830). The largest difference belonged to Innovation which was -17.850 (±9.000).

Table 10: The mean difference and standard deviation in angulation from tooth scores for brackets for the 4 mm script.

Bracket	Mean (±SD)
Bioquick	0.1322 (±0.824)
Innovation	-5.954 (±10.533)
Victory	-2.824 (±6.584)

Table 10 describes the mean combined angular difference of the combined mesial and gingival angle for each bracket brand at the 4 mm script. Here Bioquick shows the smallest overall angular difference at 0.1322 (±10.824) and the largest overall angular difference is displayed by Innovation at -5.954 (±10.533).

Table 11: The mean differences for the combined brackets for the 4 mm script at the mesial and gingival angle.

Angle	Mean (±SD)
Mesial Angle	-5.658 (±8.941)
Gingival Angel	-7.027 (±15.161)

The combined angular differences for the 4 mm script were more at the gingival angle -7.027 (±15.161) than at the mesial angle were the value was -5.658 (±8.941).

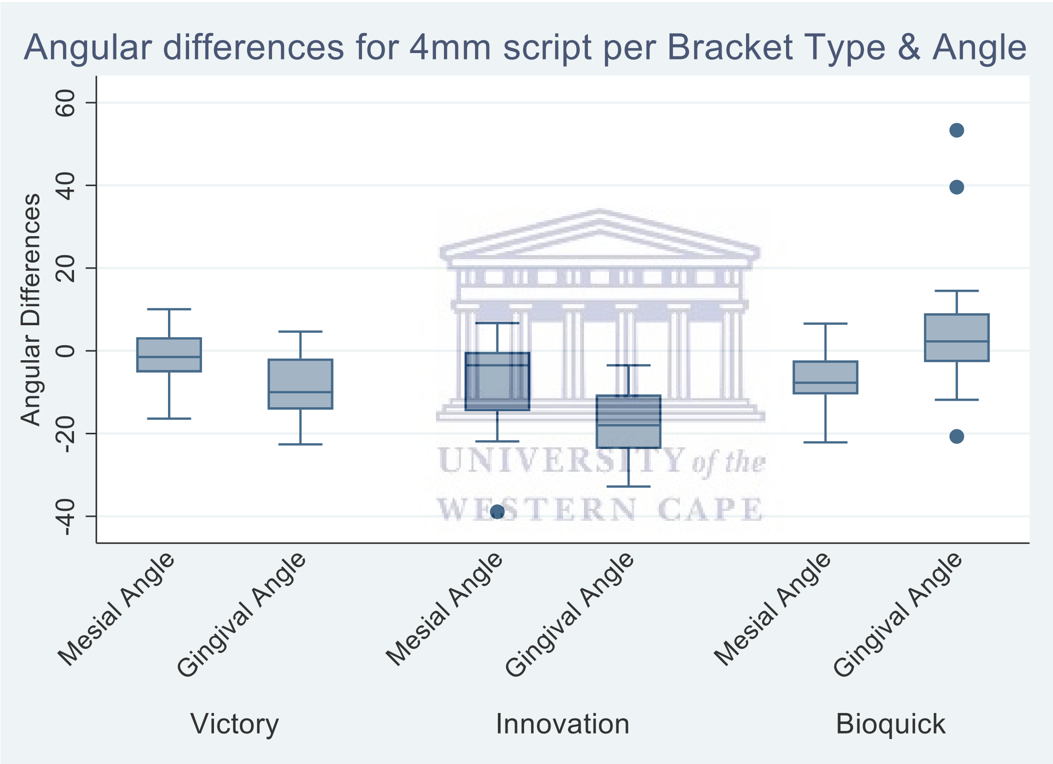

Figure 15: Box plot of the 4 mm script showing the angular differences for the brackets and the teeth. The outliers were shown as a blue dots and have been included.

Each box represents (the interquartile area) the angular differences for each bracket, at either the mesial or gingival angle. The outliers were displayed as blue dots and the medians of each group of readings are displayed by the blue line. The gingival angle of Bioquick had the greatest number of outliers 3, as compared to 1 outlier for the mesial angle of the Innovation. The box illustrating the smallest range of differences was the mesial of the Victory series. The box illustrating the greatest range of differences was the gingival of Innovation. For the medians of the mesial differences, Victory series was closest to zero followed by Innovation and finally Bioquick. The median for Bioquick at the gingival angle was closest to zero as compared to that of Innovation and Victory at the gingival angle. The median of Innovation at the gingival angle was the greatest from zero.

The results of the two-way ANOVA discovered a statistically significant interaction between bracket type and angle position on the difference in angulation from the tooth, F (6, 216) = 11.63, $p < 0.001$, partial $\eta 2 = 0.244$. Therefore, an analysis of simple main effects for bracket type was performed with statistical significance receiving a Bonferroni adjustment and being accepted at the $p < 0.025$ level. There was a statistically significant difference in mean angular difference from tooth for the different brackets, F(2, 216) = 11.46, $p < 0.0001$, partial $\eta 2 = 0.095$, and for different angle position, F(3, 216) = 15.22, $p < 0.0001$, partial $\eta 2 = 0.175$.

All pairwise comparisons were run for each simple main effect with reported 95% confidence intervals and p-values Bonferroni-adjusted within each simple main effect. Mean Difference in angulation from tooth scores for Victory Series, Innovation and Bioquick was -2.82 (±6.58), -5.95 (±10.53) and 0.13 (±10.82), respectively. Mean difference in angulation from tooth scores for the mesial angle and the gingival angle were -5.66 (±8.94) and -7.03 (±15.16) respectively.

4.6.1 Mesial Angle

The angular difference between the bracket and the tooth for Victory Series (3M Unitek) at the mesial margin was -2.037 (±6.783) and the angular difference for Innovation (GAC) at the mesial angle was -7.579 (±10.858). The pairwise comparison between the Victory Series and Innovation brackets at the mesial margin angle showed an angular difference of -5.541 (SE±2.543), p = 1. This showed that a statistically significant difference was not present between these brackets.

The angular difference between the bracket and the tooth for Victory Series at the gingival margin was -2.037 (±6.783) and the angular difference for Bioquick at the mesial angle was -7.358 (±8.002). The pairwise comparison between the Victory

Series and Bioquick brackets at the mesial margin angle showed an angular difference of -5.320 (SE±2.543), p = 1. This showed that a statistically significant difference was not present between these brackets.

The angular difference between the bracket and the tooth for Innovation at the mesial margin was -7.579 (±9.227) and the angular difference for Bioquick at the mesial angle was -7.358 (±8.002). The pairwise comparison between the Innovation and Bioquick brackets at the gingival margin angle showed an angular difference of 0.221 (SE±2.543), p = 1. This showed that a statistically significant difference was not present between these brackets.

4.6.2 Gingival Angle

The angular difference between the bracket and the tooth for Victory Series at the gingival margin was -8.649 (±7.810) and the angular difference for Innovation (GAC) at the gingival angle was -17.810 (±9.000). The pairwise comparison between the Victory Series and Innovation brackets at the gingival margin angle showed an angular difference of 1.291 (SE±2.543), p = 1. This showed that a statistically significant difference was not present between these brackets.

The angular difference between the bracket and the tooth for Victory Series at the gingival margin was -8.649 (±7.810) and the angular difference for Bioquick at the gingival angle was 5.417 (±16.830). The pairwise comparison between the Victory Series and Bioquick brackets at the gingival margin angle showed an angular difference of 14.066 (SE±2.543), p = 0. This indicated a significant difference between the two bracket types.

The angular difference between the bracket and the tooth for Innovation at the gingival margin was -17.810 (±9.000) and the angular difference for Bioquick at the gingival angle was 5.417 (±16.830). The pairwise comparison between the Innovation and Bioquick brackets at the gingival margin angle presented an angular difference of 23.267 (SE±2.543), p = 0. This indicated a significant difference between the two bracket types.

4.7 Results for the 3 mm Script

Table 12:Statistical information for the 3 mm on the angular difference of the brackets at the mesial and gingival margin.

	Angular Difference(°)	
Bracket	**Mesial Angle (±SD)**	**Gingival Angle (±SD)**
Bioquick	-5.969 (±5.044)	6.404 (±7.822)
Innovation	-4.135 (±5.550)	-11.074 (±8.302)
Victory Series	-1.062 (±4.689)	-2.574 (±7.704)

Table 12 shows the mean angular differences for the three bracket brands at the mesial and gingival angle for the 3 mm script. The smallest difference is at the mesial of the Victory series bracket at -1.062 (±4.689). The largest difference for the mesial angle was that of Bioquick which was -5.969 (±5.044). The smallest angular difference at the gingival angle was Victory Series at 2.574 (±7.704).The largest difference belonged to Innovation which was -11.074 (±8.302).

Table 13: The mean difference and standard deviation in angulation from tooth scores for brackets for the 3 mm script.

Bracket	**Mean (±SD)**
Bioquick	0.872 (±6.620)
Innovation	-3.585 (±6.905)
Victory Series	-1.245 (±4.814)

Table 13 describes the mean combined angular difference of the combined mesial and gingival angle for each bracket brand at the 3 mm script. Here Bioquick shows the smallest overall angular difference at 0.872 (±6.620) and the largest overall angular difference is displayed by Innovation at -3.585 (±6.905).

Table 14: The mean differences for the combined brackets for the 3 mm script at the mesial and gingival angle.

Angle(°)	Mean (±SD)
Mesial Angle	-3.722 (± 5.358)
Gingival Angel	-2.414 (±10.594)

The combined angular differences for the 3 mm script was less at the gingival angle -2.414 (±10.594) than at the mesial angle were the value was -3.722 (±5.358).

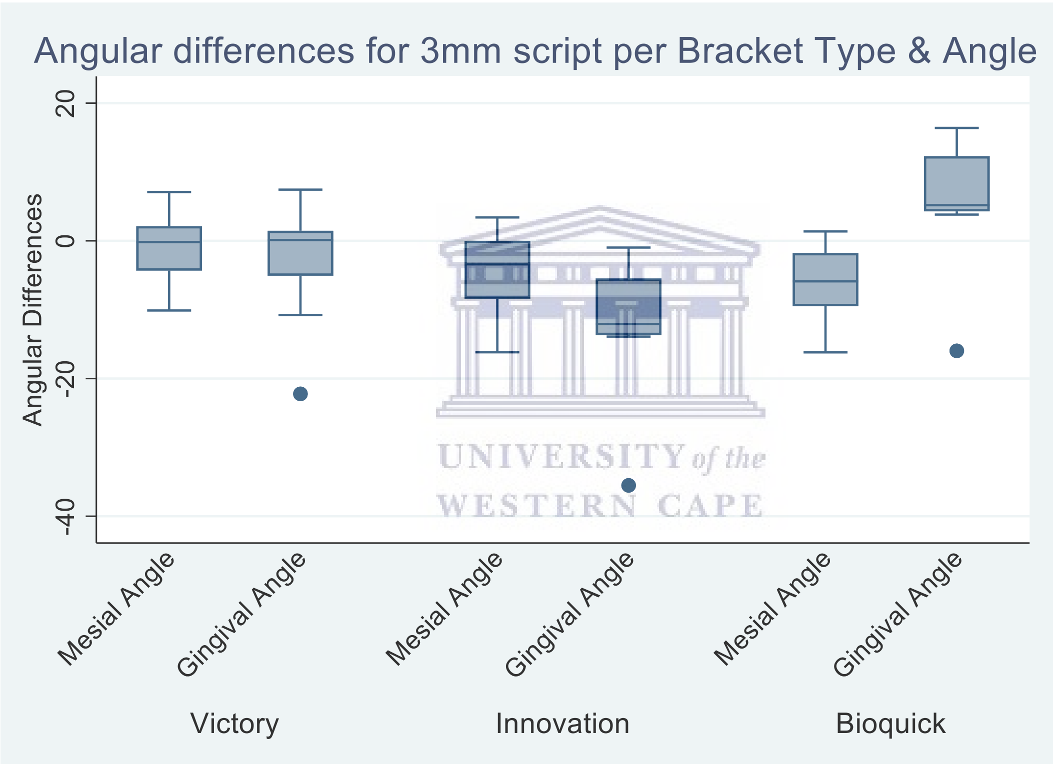

Figure 16: Box plot of the 3 mm script showing the angular differences for the brackets and the teeth. The outliers were shown as a blue dots and have been included.

Each box represents (the interquartile area) the angular differences for each bracket, at either the mesial or gingival angle. The outliers were displayed as blue dots and the medians of each group of readings are displayed by the blue line. The gingival angle of Victory series, the gingival angle of Innovation and the gingival angle of Bioquick all have one outlier. The box illustrating the smallest range of differences was the gingival angle of Innovation and the gingival angle of Bioquick. The box illustrating the greatest range of differences was the mesial of Innovation. For the medians of the mesial differences, Victory series was closest to zero followed by Innovation and finally Bioquick. The median for Victory series at the gingival angle was closest to zero as compared to that of Innovation and Bioquick at the gingival angle. The median of Innovation at the gingival angle was the greatest from zero.

The results of the two-way ANOVA for the 3 mm script revealed a statistically significant interaction between bracket type and angle position on the difference in angulation from the tooth, $F(6, 156) = 12.76$, $p < 0.001$, partial $\eta 2 = 0.33$. Therefore, an analysis of simple main effects for bracket type was performed with statistical significance receiving a Bonferroni adjustment and being accepted at the $p < 0.025$ level. There was a statistically significant difference in mean angular difference of the tooth for different brackets, $F(2, 156) = 11.35$, $p < 0.0001$, partial $\eta 2 = 0.13$, as for different angle position, $F(3, 156) = 12{,}76$, $p < 0.0001$, partial $\eta 2 = 0.14$.

All pairwise comparisons were run for each simple main effect with reported 95% confidence intervals and p-values Bonferroni-adjusted within each simple main effect. Mean angular difference in tooth scores for Victory, Innovation and Bioquick was -1.25 (±4.81), -3.59 (±6.9)1 and 0.87 (±6.62), respectively. Mean difference in angulation from tooth scores for the mesial angle and gingival angle was -3.72 (±5.38) and -2.41 (±10.59), respectively.

4.7.1 Mesial Angle

The angular difference between the bracket and the tooth for Victory Series at the mesial margin was -1.062 (±4.689) and the angular difference for Innovation at the mesial angle was -4.135 (±5.550). The pairwise comparison between the Victory Series and Innovation brackets at the mesial margin angle showed an angular difference of -3.073 (SE±1.871), $p = 1$. This showed that a statistically significant difference was not present between these brackets.

The angular difference between the bracket and the tooth for Victory Series at the gingival margin was -1.062 (±4.689) and the angular difference for Bioquick at the mesial angle was -5.969 (±5.044). The pairwise comparison between the Victory Series and Bioquick brackets at the mesial margin angle showed an angular difference of -4.907 (SE±1.871), p = 0.63. This showed that a statistically significant difference was not present between these brackets.

The angular difference between the bracket and the tooth for Innovation at the mesial margin was -4.135 (±5.550) and the angular difference for Bioquick at the mesial angle was -5.969 (±5.044). The pairwise comparison between the Innovation and Bioquick brackets at the gingival margin angle showed an angular difference of -1.833 (SE±1.871), p = 1. This showed that a statistically significant difference was not present between these brackets.

4.7.2 Gingival Angle

The angular difference between the bracket and the tooth for Victory Series at the gingival margin was –2.574 (±7.704) and the angular difference for Innovation at the gingival angle was -11.074 (±8.302). The pairwise comparison between the Victory Series and Innovation brackets at the gingival margin angle showed an angular difference of -8.5 (SE±1.871), p = 0.001. This showed that a statistically significant difference was present between these brackets at the 3 mm script.

The angular difference between the bracket and the tooth for Victory Series at the gingival margin was -2.574 (±7.704) and the angular difference for Bioquick at the gingival angle was 6.404 (±7.822). The pairwise comparison between the Victory Series and Bioquick brackets at the gingival margin angle showed an angular difference of 8.978 (SE±1.871), p = 0. This indicated a significant difference between the two bracket types.

The angular difference between the bracket and the tooth for Innovation at the gingival margin was -11.074 (±8.302) and the angular difference for Bioquick at the gingival angle was 6.404 (±7.822). The pairwise comparison between the Innovation and Bioquick brackets at the gingival margin angle presented an angular difference of

17.478 (SE±1.871), p = 0. This indicated a significant difference between the two bracket types.

Chapter 5

Discussion

This dissertation investigated how the curvatures of 3 orthodontic bracket brands related to the buccal curvatures of 33 maxillary second premolars using micro computed tomography. The methodology used in this dissertation is novel, since no preceding studies can be found that relates the curvatures of commercially available orthodontic brackets to that of their corresponding teeth. The importance of the study is the interplay relationship of the orthodontic bracket base to the curvature of the corresponding area on the tooth. This interplay is of vital importance as similar curvatures will lead to better adaptation of the bracket on the tooth. Better adaptation will lead to an increase in sheer bond strength, which will lead to an increased ability to endure orthodontic and masticatory forces. This is underlined by a higher sheer bond strength shown in custom made CAD/CAM produced orthodontic brackets as compared to conventional orthodontic brackets (Sha H-N et al., 2018).

The results of this dissertation indicated that there were a significant difference in curvature amongst the orthodontic brackets in the sample and in the variation amongst the curvature of the premolars. Hence, the null hypothesis that there would be a significant difference between the curvatures of the randomly selected sample of pre-molars in relation to the curvatures of the bracket bases of the three brands, was accepted.

If the curvature of the bracket does not follow the curvature of the tooth, it may result in the decreased adhesion, retention and consequently efficacy of the orthodontic appliance (Gonjito et al., 2004). When adaptation is poor, a greater amount of adhesive is required to fill the space between the tooth and the bracket base which could lead to an increase in polymerisation shrinkage. The poor adaptation could also lead to gap formation at the bracket-enamel-adhesive interface, which can lead to microleakage and a lower bond strength (Arhun et al., 2006). It has been shown in the literature review that it could result in the formation of white spot lesions beneath and around the bracket base. Poor adaptation to the tooth can also result in the incorrect placement of the bracket. Germane et al., (1989) found the effective torque of a bracket was influenced by the difference in tooth morphology and the bracket base and also found that the amount of effective torque acting on the tooth varied when the bracket was placed at different heights.

This discussion chapter will illustrate the variability of the curvature among the brackets, the teeth and the angular differences between them and how these factors are related to adaptation, microleakage, white spot formation and retention.

5.1 Variations in Bracket Base Curvature

When analysing commercial manufacturer catalogues of orthodontic brackets, very little information is provided with regards to the angulation of the mesio-distal or occluso-gingival dimensions of the attachments. This is despite the curvature of the bracket base being a vital component for effective use of the straight-wire appliance (Gonjito et al., 2004). Gonjito et al., (2004) investigated the curvatures of 4 commercially available orthodontic brackets brands (A-Company; Abzil-Lancer; Morelli and Unitek) and found, no standard angulation of the bracket bases. This was in agreement with the findings of this dissertation which found variations in the mesio-distal and occluso-gingival curvature angles (Table 4) of the three brands assessed. The largest difference between Bioquick and Innovation at the gingival angle was 17º. The discrepancies at the mesial angle were less with the largest being between Victory series (14.78°) and Bioquick (11.12°). The variations in curvature was also confirmed by the findings Vianna et al., (2005) who investigated the morphology of maxillary canine attachments and again found no standardisation between A-Company; Abzil-Lancer; Morelli and Unitek brackets.

5.2 Variations in Tooth Curvature

Andrews (1976) stated that only a very small variation existed in tooth morphology and it would not impact the implementation of the straight-wire appliance. This was refuted by multiple authors such as Delinger (1978), Germane et al., (1989) and Meithke and Melsen (1999), who found the variations in tooth morphology to be greater than the variation in pre-adjusted appliances. This study found mean mesial curvature of the maxillary second premolar for the combined 4 mm and 3 mm scripts to be 18.103°

(SD±7.426) (Table 5) with a coefficient of variation of 41.21%. This corresponded with the findings of Miethke and Melsen (1999) found the curvature of the maxillary premolar at the mesial margin to be -0.0102 (±0.0050) with a coefficient of variation of 41.67%. Watanabe and Koga (2001) found the mean curvature of the maxillary second premolar to be 11.03 mm (SD±3.82) is showed a coefficient of variation to be 34.63%.

These findings elude to a great variation in curvature in the occluso-gingival direction. The mean gingival angle found in this study was 56.383° (SD±10.672) (Table 5) with a coefficient of variation of 18.92%. This showed a lesser degree of variation of curvature in the horizontal direction as compared to the vertical direction, for the maxillary second premolar. This was similar to the findings of Watanabe and Koga (2001) who found the mean curvature of the upper second premolar to be 3.79 mm (SD±0.38) with a coefficient of variation of 10.02%. The angular readings of the teeth at the gingival margins were greater but showed a lesser degree of variation than the angles at the mesial margin.

This was highlighted by the results of the one-way ANOVA f (3.92) =1218.92, p > 0.001 which showed a statistically significant difference in mesial and gingival angles.

5.3 Angular Differences:

The angular difference between the bracket and the tooth is the difference in degrees between angles of the bracket and the corresponding angle on the tooth. It is an indicator of how similar curvature the bracket and the curvature of the teeth are. According to Gonjito et al., (2004), if the curvature of the bracket does not follow the curvature of the tooth, it may result in the decreased adhesion, retention and consequently efficacy of the orthodontic appliance. Vianna et al., (2005) used finite element analysis to investigate the influence of bracket base curvature on force resistance of 4 different bracket brands. The bracket which most closely followed the curvature of the tooth showed greater uniformity in sheer stress distribution and experience less adhesion failure as result of torsional forces as compared to the brackets which had showed poorer adaptation to the tooth. This showed a direct relation between the curvature of the bracket base, the adaptation of the bracket to the buccal surface of the tooth and its resistance to applied forces. The possibility of improved bracket adaptation leading to better retention is also eluded to by Sha et al., (2018). They investigated the sheer bond strength and debonding force required to displace custom brackets and conventional brackets. Both labial and lingual custom CAD/CAM manufactured brackets and labial and lingual conventional brackets were bonded to upper maxillary premolars and a force was applied using a universal testing machine. The results showed a higher force was required to debond the custom labial and lingual brackets as compared to the conventional bracket counterparts. The sheer bond strength was also higher for the custom brackets as compared to the conventional brackets (Sha et al., 2018). This agreed to the findings of Weber (2011) who investigated the effectiveness and efficiency of custom manufactured brackets versus conventional brackets and found less debonding in the custom bracket group. Jain et al., (2013) investigated the effect of a variation in adhesive thickness under the orthodontic bracket and its relation to sheer bond strength. They found an inverse relation between the adhesive thickness and sheer bond strength. The sheer bond strength increased as adhesive thickness decreased from 0.99 mm to 0.83 mm. However, this changed to a reduction in sheer bond strength when thickness of the adhesive was below 0.83 mm. This also highlights the importance of proper adaptation of the orthodontic bracket on the tooth in order to prevent excessive adhesive between the tooth and the bracket.

In this dissertation the angular differences were calculated for the joint 4 mm and 3 mm scripts, at the 4 mm as well as the 3 mm scripts. For the joint scripts (samples of teeth of 3 and 4 mm combined) at the mesial angle, the bracket with the lowest mean angular difference was Victory series -1.623 (SD±5.920) indicting the bracket underestimated the curvature of the tooth. This was the bracket, which most closely matched the mean curvature of the teeth at the mesial angle for the joint script. The largest mean angular difference was that of Bioquick -6.796 (SD±6.844), indicating greater underestimation of the curvature of the tooth. The results of the Bonferonni pairwise comparison between the brackets -5.145 (SE±1.681), p = 0.156 did not show a statistically significant difference. Innovation -6.118 (SD±9.045) also underestimated the tooth and the pairwise comparison between Victory series and Innovation was also statistically insignificant with an angular difference of -4.494(SE±1.681), p = 0.517. The angular differences at the 4 mm script, also showed Victory series to have the lowest difference -2.037 (SD±6.783) and hence showing the best match for the curvature of the teeth while still underestimating the tooth curvature. The largest angular difference was that of Innovation -7.579 (SD±10.858). The Bonferonni pairwise between Victory series and Innovation produced a difference of-5.541 (SE±2.543), p = 1, which again was not statistically significant. This was similar to the pairwise comparison between Victory series and Bioquick which was -5.320 (SE±2.543) p = 1. The results of the 3 mm script were similar to that of the joint and 4 mm script. With all brackets all the brackets underestimating the tooth curvature, Victory Series -1.062 (SD±4.689), Bioquick -5.69 (SD±5.044) and Innovation -4.135 (SD±5.550). The lowest angular difference was Victory series and the largest was Bioquick. The pairwise comparisons between Victory series and Innovation -3.073 (SE±1.871), p = 1 and between Victory series and Bioquick 4.907 (SE±1.871), p = 0.63 were both not statistically significant. These results elude a slightly better adaptation of the Victory series bracket at the mesial margin of the tooth, but this is not statistically significant for joint, 4 mm and 3 mm, indicating a similar level of adaptation for all brackets at the mesial margin.

The angular measurements of the gingival angle were far greater than the mesial angle (Variations in Tooth Curvature). The bracket with the lowest angular difference at the gingival margin for the joint scripts was Bioquick 5.836 (SD±13.580) which overestimated the tooth curvature. The largest angular difference was Innovation -14.975 (SD±9.227), which greatly underestimated the curvature of the tooth. The results of the pairwise comparison between Bioquick and Innovation was 20.811(SE±1.681) p = 0, which was statistically significant. This was similar to the results of the 4 mm script at the gingival margin where Bioquick had the lowest angular difference and overestimated the tooth curvature by 5.417 (SD±16.830). Innovation underestimated the tooth curvature by -17.850 (SD±9.000). The pairwise comparison between Bioquick and Innovation highlighted this with a statistically significant difference of 23.267 (SE±2.543), p = 0. These results indicated that a greater degree of curvature of the bracket at the gingival margin, could lead to better adaptation as Bioquick had the largest gingival angle (Table 4). However, the lowest angular difference at the 3 mm script for the gingival angle was that of Victory series -2.574 (SD±7.704), underestimating the tooth curvature. The largest angular difference was Innovation, underestimating the tooth by -11.074 (SD±8.302). The pairwise comparison between Victory series and Innovation at the 3 mm gingival margin was -8.500 (SE±1.871), p = 0.01 was statistically significant. The performance of Victory series at the 3 mm script could be due to a decrease in horizontal curvature for shorter teeth and due to Victory series having a lesser degree of curvature than Bioquick (Table 4). The results show the worst adaptation at the gingival margin being that of Innovation, this could lead to a large gap between the bracket base and the enamel interface. This will result in a larger amount of adhesive required to fill this space and according to Arhun et al., 2006 could leading to a greater chance of microleakage. The increased microleakage could result in demineralisation under the orthodontic bracket at the gingival margin and white spot lesion formation (James, 2003). However more specific investigation will be required to confirm the correlation between the angular difference and white spot formation.

Chapter 6

Conclusion

This dissertation made use of a novel method of comparing the Micro-CT images of the curvatures of orthodontic brackets to the buccal curvature of the Micro-CT premolars, in order to establish the discrepancy between the three bracket brands.

The results correlated well with the literature and also concluded that there exist a lack of standardisation of orthodontic bracket base curvature between different brands for the maxillary second premolar. For the randomly selected sample of teeth a significant amount of variation was found in the curvature of the maxillary second premolar in both horizontal and vertical directions. This agreed with the findings of Miethke and Melsen (1999) and Watanabe and Koga (2001).

The results of this dissertation found the lowest angular difference at the mesial angle for all scripts (both 3 and 4 mm) to be that of Victory series, hence indicating the best adaptation to the randomly selected teeth. This was followed by Innovation and Bioquick who were evenly matched with no significant difference. The best adapting bracket in a gingival direction was Bioquick for the joint 3&4 mm scripts as well as the 4 mm scripts. The bracket with the largest angular difference in the gingival area was that of Innovation. The best performing bracket at the gingival angle for the 3 mm script was Victory series. Victory series was the best all round performing bracket for both the mesial and gingival angles. The clinical relevance of this dissertation was bringing the results closer to the established literature and concurred that a better bracket-to-tooth adaptation could result in an increased retention, a decreased amount of resin material between the enamel and the bracket base and consequently the decrease in the potential of microleakage and subsequent WSLs formation. This in essence can result in better overall efficiency of the orthodontic fixed appliance.

6.1 Limitations

A limitation of this study would be the size of the sample. The manufacturers of orthodontic brackets would likely use a larger sample of teeth from various ethnical backgrounds to attain a more global reflection of the variations in the curvature of the second maxillary premolar. This can lead to the creation of ideal curvature values in a mesio-distal and occluso-gingival direction which can serve as a standard for bracket manufactures. A larger sample could also factor in variables such as gender and ethnicity to assess its influence on the variations in tooth curvature. A larger sample of brackets from different manufacturers could have increased the number of comparisons possible and provided greater information to the variations in manufacturer designs. However, this scale of study was not the objective of this dissertation. This study could not definitively state the influence of bracket curvature to formation of WSLs and microleakage, although the literature shows a correlation. It is suggested that further investigations be done to define the influence of bracket base curvature and the formation of WSLs.

6.2 Recommendations

Due to the lack of literature on orthodontic bracket base curvature and methodologies that are accurate and reproducible, it is suggested that more investigations be performed in relation to the influence of bracket base curvature on adaptation, sheer bond strength and polymerisation shrinkage. This Micro-CT method described in this dissertation is an accurate analysis method for use in future studies. The use of cone beam computed tomography (CBCT) images instead of plaster models could also be recommended, but the scatter from the orthodontic brackets and the accuracy below 1 mm compared to the well-established accuracy of Micro-CT. The advantage is that if CBCT images can be saved in the correct format, it will enhance scan collection from various genders and ethnicities across the world. The CBCT of teeth are more accurate than plaster casts of teeth (Hajeer et al., 2016) and could also allow for an increase in sample size as CBCT images can be taken from archived files.

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