**The Use of CBCTs to Determine Relative Anchorage Values by Measuring Maxillary Root Surface Areas within Bone**

A THESIS

Presented to the Faculty of

Uniformed Services University of the Health Sciences

In Partial Fulfillment

Of the Requirements

For the Degree of

MASTER OF SCIENCE

By

Jonathan Y. Stateson, DDS

San Antonio, TX

Jun 30, 2019

The views expressed in this study are those of the author and do not reflect the official policy of the United States Army, the Department of Defense, or the United States Government. The author does not have any financial interest in the companies whose materials are discussed in this article.

**The Use of CBCTs to Determine Relative Anchorage Values**

**by Measuring Maxillary Root Surface Areas within Bone**

Jonathan Y. Stateson, D.D.S.

APPROVED:

[redacted]

Chad Burton, D.D.S., Supervising Professor

[redacted]

Ryan L. Snyder, D.D.S., M.S., Program Director

[redacted]

Brian W. Penton, D.D.S., M.S., Chairman

3/19/2019

Date

APPROVED:

[redacted]

Jay D. Graver, D.M.D., M.S., Dean, Air Force Postgraduate Dental School

# ACKNOWLEDGEMENTS

I would like to acknowledge Dr. Chad Burton for his mentorship and guidance throughout this investigation. I would also like to recognize Mr. Dan Sierra for his expertise in navigating through Materialise Mimics (Leuven, Belgium) and Geomagic® Freeform® Plus (Rock Hill, SC) software to outline root surfaces of maxillary teeth. Thank you to the faculty and co-residents for constant encouragement and insight to allow this investigation to come to fruition.

# DEDICATION

This thesis is dedicated to my loving family. To my beautiful wife and children for their constant support and love throughout my endeavors. To my parents, for their lifelong encouragement. To my wife's parents, who assisted in providing care to my daughters Eden and Ella.

# COPYRIGHT STATEMENT

The author hereby certifies that the use of any copyrighted material in the thesis manuscript entitled:

“**The Use of CBCTs to Determine Relative Anchorage Values by Measuring Maxillary Root Surface Areas within Bone**”

is appropriately acknowledged and, beyond brief excerpts, is with the permission of the copyright owner.

[redacted]

Jonathan Y. Stateson, D.D.S., MAJ, US ARMY, DC
Tri-Service Orthodontic Residency Program
Air Force Post Graduate Dental School
June 2019

Distribution Statement

Distribution A: Public Release.

## ABSTRACT

**INTRODUCTION:** Anchorage is vital in both controlling tooth movement and understanding pressure distribution from force application. Relative anchorage value (RAV), as defined by the authors, is the root surface area (SA) below crestal bone.

**OBJECTIVE:** The purpose of this study is to use CBCTs to determine RAVs of teeth by measuring and comparing the root SA of anterior to posterior teeth. These values will be compared to the modified Freeman study cited by Dr. Proffit in Contemporary Orthodontics.

**MATERIALS AND METHODS:** A retrospective study reviewed images captured on 3D Accuitomo 170 (Irvine, CA), ranging from small FOV (40x40mm) to large FOV (170x120mm). Digital Imaging and Communications in Medicine (DICOM) files meeting the inclusion criteria were transported into Materialise Mimics (Leuven, Belgium) to outline and isolate root structure from alveolar bone. Stereolithography (STL) files from Mimics was then imported into Geomagic Freeform Plus (Rock Hill, SC) to analyze root surface area below crestal bone. RAVs of posterior teeth were compared to anterior teeth for a first premolar extraction scenario. In addition, a ratio was calculated to allow for comparison of RAVs from this study to anchorage values from the modified Freeman study.

**RESULTS:** Maxillary RAV (mm2): central-159, lateral-137, canine-223, 1st premolar-178, 2nd premolar-170, 1st molar 370, and 2nd molar 326. Mandibular RAV (mm2):

central-120, lateral-145, canine-217, 1st premolar-172, 2nd premolar-178, 1st molar 408, and 2nd molar 322. The posterior anchorage (excluding 1st premolars) was 62.5% of the total anchorage compared to 63.7% in the Freeman study. For the mandible, the percent of posterior anchorage (excluding 1st premolars) was 65.3% compared to 64.5% in the Freeman study.

**CONCLUSION:** This study demonstrates CBCTs can be used to determine RAVs for teeth meeting the inclusion criteria. In addition, our study agrees with the results from Freeman. RAV may aid the clinician in better understanding and individualizing treatment objectives to meet the patient's anchorage requirements.

# TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# I. INTRODUCTION

## A. Anchorage-historical

Anchorage can be defined as “the resistance of unwanted tooth movment”.[1] Newton’s third law states that for every action, there is an equal and opposite reaction. Baker *et al.* described anchorage in terms of Newton’s third law as the equal and opposite force opposing those teeth being retracted or moved.[2]

Anchorage is not a novel concept to orthodontists who must manage appropriate mechanics to allow for desired tooth movement. In 1907, Edward H. Angle, considered to be the “Father of Orthodontics,” believed anchorage to be a vital component in the efficient use of orthodontic appliances.[3] Angle stated “the resistance of the anchorage must be greater than that offered by the tooth to be moved."[4] Failure to meet this requirement will result in displacement of the anchor segment.

Charles Tweed, a disciple of Angle, contrasted with Angle’s non-extraction philosophy. Treatment planning of extraction spaces requires greater emphasis on anchorage requirements and one of Tweed’s many contributions was developing a concept of orderly treatment and introducing anchorage preparation.[3]

Anchorage is acquired through a variety of sources: intraoral, extraoral and skeletal anchorage. Intraoral anchorage, according to Baker *et al.,* is comprised of alveolar bone, teeth, dental arches, palatal and basal bone and lip musculature.[2] Mandibular molars present a more difficult movement compared to maxillary molars due to the thicker cortices and less trabecular bone.[3] Teeth, and their corresponding root form and size, are a vital component to achieving desired tooth movement. Increasing the number of teeth into the anchorage segment will allow for greater reinforced anchorage. Ankylosed teeth also provide a source of anchorage. Angelopoulou MV *et al.* demonstrated the protraction of a permanent first molar following induction of the primary second molar to become ankylosed.[5] Dental arches are commonly used for anchorage to classify buccal segments via inter-maxillary elastics. Orthodontic appliances, such as a Nance, can utilize palatal bone to bolster posterior anchorage segments. Other appliances such as the lip bumper and Frankel, harness the forces from lip musculature to achieve desired tooth movement.

Extraoral anchorage is typically derived by use of headgear appliances with the calvarium or cervical skeletal components providing anchorage to achieve desired growth modification and/or dentoalveolar movement. A disadvantage of headgear is patient cooperation. Non-compliant patients will prolong treatment or require alternative orthodontic mechanics to achieve desired treatment objectives.

Skeletal anchorage was historically limited to the anterior palate and headgear.[6] More recently, skeletal anchorage has become synonymous with temporary anchorage devices (TADs). TADs can be utilized to correct some of the downfalls of headgear, such as compliance and heavy intermittent forces.[6] When treatment planning, the clinician must determine the anchor teeth and type of anchorage that will be utilized during treatment.

The various sources of anchorage currently present in modern orthodontics was not always available to clinicians. A shift in the views of anchorage occurred in the 1970's. The classical concept of anchorage management involved use of an appliance, such as headgear.[2] The new concept of anchor management utilized teeth themselves to provide differential anchorage values. This allowed for differential application of force, resulting in preferential movement of teeth.[2] The preferential movement of teeth can be considered a function of root surface-area and bone contact-area.[3] It is therefore important to understand root surface area because orthodontic tooth movement is a function of the periodontal ligament (PDL) and its surrounding alveolar bone.

**B. Types of anchorage**

Reciprocal tooth movement occurs when equal movements of arch segments are desired. For this situation, equal force distribution to the PDL of arch segments results in equal and opposite space closure.[6] A common tooth to be extracted is the maxillary first premolar. Based on anchorage values, we can expect reciprocal closure, i.e. equal but opposite movement, if the first molar and second premolar are the posterior anchor segment. This is due to the roughly equal root surface areas of the anterior and posterior segments.

Reinforced anchorage is encountered when differential movement of arch segments is desired. For this particular situation, the inclusion of additional teeth to the anchorage arch segment will increase the root surface area, decreasing the pressure within the PDL of the anchorage arch segment, resulting in less movement of the anchorage arch segment.[6] Preferential advancement of the mandibular molars and preferential retraction of the maxillary anterior segment allow for correction of a dental Class II malocclusion following extraction of maxillary first premolars and mandibular second premolars.

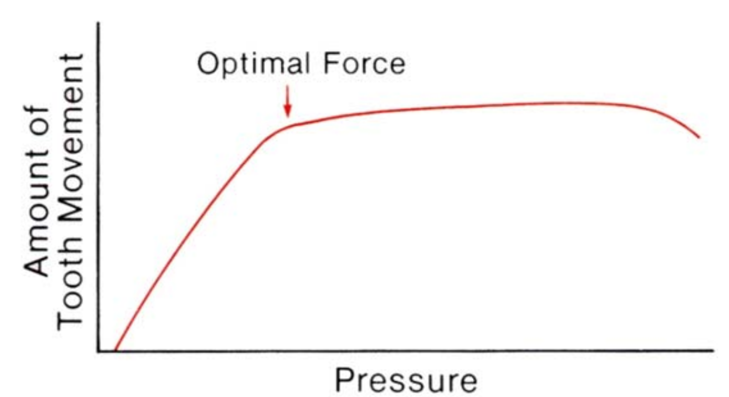
Stationary anchorage involves the bodily movement of one group of teeth against tipping of another group of teeth.[6] Preferential tooth movement for this type of anchorage is attributed to the more difficult movement that is accompanied with translation and the easier movement that is achieved with tipping.[6]

Cortical anchorage is the attempt to control tooth movement with the facial and lingual cortical plates.[6] The idea behind this type of anchorage is that the more dense cortical bone is more resistant to resorption than the less dense medullary bone.[6]

**C. Tooth movement and anchorage**

Anchorage also involves biologic components such as cementum, PDL, and bone.[2] The density of alveolar bone, patient's age, occlusal forces, soft tissue support, parafunctional habits, and anchorage values of roots are some of the factors that have an effect on tooth movement. Force must be applied in order to overcome the resistance to movement, and this force is also responsible for initiating bone remodeling which allows for tooth movement.[6] Anchor teeth, which can be thought of as the segment of teeth that the clinician prefers not to move, are capable of responding to force the same way as the non-anchor teeth, thus, controlling these forces is an important aspect of anchorage control.[6] According to Storey and Smith[7], excessive force can result in movement of the anchor segment, and suboptimal force results in inefficient tooth movement of non-anchor teeth.

One strategy for controlling anchorage is the selective application of force, *i.e.* concentrate the force where tooth movement is desired and dissipate the reactionary force over as many other teeth as possible.[6] Selectively applying less pressure to the PDL of anchor teeth creates a differential response, whereby the teeth with greater pressure produce more tooth movement than the teeth with less pressure.[6] According to Proffit, pressure in the PDL is determined by the force applied to a tooth divided by the area of the PDL over which that force is distributed.[6] This is analogous to the physics principal of pressure equaling force divided by the area of application. Accordingly, increasing the pressure will result in increasing the amount of tooth movement.[6] This relationship does, however, meet a point of diminishing returns beyond optimal force application.[6]



Proffit WR FH, Sarver DM. Contemporary Orthodontics. 5th ed. St. Louis: Mosby; 2013

Figure 01 - Pressure Response Curve

As evident in the diagram above (Figure 01), excessive force can result in anchorage loss due to the increase in force dispersed among the anchor segment, which results in mesial movement of the molars of the anchor segment.[2]

One method for assessing root surface anchorage is identification of the anchorage value of a tooth, which Proffit describes as the resistance to movement.[6] According to Proffit, anchorage can be thought of "as a function of its root surface area, which is the same as its PDL area".[6] The below figure (Figure 02 - as modified from the Freeman study[6, 8]) shows the anchorage values of teeth and demonstrates that the anchorage value of a particular tooth is approximately equivalent to its root surface area.[8]

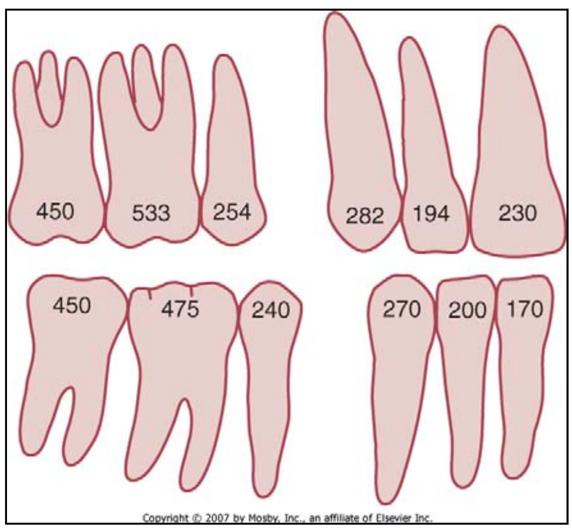



Figure 02 - Modified Freeman Anchorage Values

By understanding the anchorage values of the teeth, the clinician can take appropriate measures to conserve anchorage by reducing stress on the PDL of anchorage segments and placing more stress on the teeth planned for movement.[9] Increasing the root surface area of the anchor segment, such as the addition of teeth into the segment, or decreasing the number of teeth to be moved accomplishes this anchorage conservation.[9] From the above figure you can see that the combined values of the first molar and second premolar are roughly equal in surface area to the anterior teeth.[6]

**D. Anchorage Intervention**

One strategy to control anchorage is through reinforcement with additional teeth. Addition of teeth into the anchor segment will increase the PDL surface area, decrease the pressure to the PDL which then decreases the amount of movement of the anchor unit. For significant differential tooth movement to occur a ratio of 2:1 is desired without sliding mechanics and 4:1 with it (ratio is the PDL area of anchorage segment to the PDL area of tooth movement segment).[6] A value less that 2:1 will result in reciprocal closure.[6]

Another strategy to maximize anchorage control is to consider subdivision of the desired movement. In the case of closing a premolar extraction space, rather than closing *en masse*, retracting the canine first and then adding it to the posterior anchorage for retracting the remaining anterior teeth will allow for greater anterior retraction.[6] This is a method used in the original Tweed technique. Alternatively, the Begg technique allows for teeth to tip into the extraction space, and in the later stage of treatment they will be positioned upright. In this situation, the anterior teeth will tip distally against the bodily movement of the posterior teeth and later the roots of the anterior teeth would be torqued into proper position.[6]

## E. Root Surface Area and CBCT

Historically, one method for root surface area analysis was with the use of conventional radiographs. With the availability of Cone Beam Computed Tomography (CBCT) and software, it is now possible to determine relative anchorage values of teeth from a three dimensional perspective.[10] One study showed the "typical dentition root surface area, excluding third molars, was 75 $cm^2$, and 95% of the dentitions had a total root surface area somewhere between 65 $cm^2$ and 86 $cm^2$."[11]

Another study investigated the possibility of measuring root surface area with traditional radiographs.[12] The investigators attempted to indirectly measure roots as either a geometric shape or by immersing the root in a solution which created a membrane encompassing the tooth that could be later removed and measured two dimensionally.[12] The investigators concluded that it was possible to use conventional radiographs to calculate root surface area with a margin of error around 10-15%.[12]

CBCT offers several advantages over conventional radiographs, such as minimal distortion, three-dimension capability and a more accurate image. Tooth roots of porcine were measured radiographically, comparing intraoral radiographs with CBCT, and the results were compared to the true measurements of the tooth roots.[13] No statistical significance was found for the differences between CBCT root measurements and the true root measurements, while the intraoral radiograph measurements were deemed less accurate.[13] An additional study illustrated the accuracy of CBCT when comparing CBCT measurements to true measurements and found that measurements for 0.40 and 0.25-voxel were accurate when compared to true measurements.[14]

Forst *et al.* demonstrated excellent intra/inter-rater reliability of 3D tooth volume measurements with CBCTs following automated segmentation with manual refinement on a 2D slice-by-slice basis in all three dimensions of space.[15] While various CBCT studies have measured roots, applying these measurements to the original anchorage values by Freeman[8] is a novel concept, especially when you consider that most previous studies performed measurements on extracted teeth.

To date, there is only one study that investigated relative anchorage values of non-extracted teeth.[10] Wright[10] and Stateson defined relative anchorage value as that portion of a tooth embedded in alveolar bone (i.e. subcrestal root surface area).[10] There were several limitations to this study: Data was collected exclusively on mandibular teeth, and no statistical analysis was performed to relate the relative anchorage values acquired from the study to the findings by Freeman. According to Wright, values from his study were 49.9 $mm^2$ to 67.2 $mm^2$ smaller for all teeth except for the second molar which demonstrated the greatest difference and was 127.6 $mm^2$ smaller when compared to the Freeman values.[10] Descriptive statistics (in the form of subtraction) was the only method employed by the author when comparing the data obtained from the study to the modified Freeman values.

## II. OBJECTIVE

The purpose of this study is to complete the findings by Wright and measure the relative anchorage values of maxillary teeth using CBCT. Data will be analyzed, and the anterior and posterior relative anchorage values will be compared to each other and to the Freeman values referenced by Proffit.

Many differences exist between the maxilla and the mandible, specifically the anatomy of bone and dental root morphology. According to Graber, the primary considerations for assessing anchorage potential are the density of alveolar bone and the cross-sectional area of the roots.[3] In general, remodeling occurs more rapidly in bones composed primarily of trabeculae than those of cortical bone.[3] The thin cortices and trabecular bone of the maxilla and the thick cortices and more coarse trabeculae of the mandible help explain why clinically the maxillary molars have less anchorage compared to mandibular molars of the same patient.[3]

From an anatomical perspective, the maxilla is vastly different from the mandible. There are no muscles that attach to the maxilla and it is loaded predominately in compression and transfers much of its load to the rest of the cranium.[3] In contrast, the mandible is subjected to torsion and flexure due to the function of the attached muscles and requires thicker cortices to resist torsional and bending strain.[3]

The maxilla offers additional anchorage in the form of the anterior palate. This is one reason why space regaining is easier in the maxilla than the mandible.[6] Skeletal Class II malocclusion patients tend to have maxillary first molars rotated mesially around the palatal root.[6] Distal tipping and de-rotation of the molars can allow for 2-3mm of space regaining.[6]

The maxilla also plays a large factor in anchorage control in non-extraction cases to correct molar classification. For example, Class II elastics result in relatively small amount of distal movement of the maxilla compared to the larger mesial movement of the mandibular teeth.[6]

For these reasons, it is beneficial to determine the relative anchorage values of maxillary root surface areas within bone with CBCTs. Together, with the known relative anchorage values of the mandibular root surface areas of a previous study[10] the clinician will be able to better understand anchorage values and to individually establish anchorage requirements for a given clinical situation.

**A. Overall Objectives**

The purpose of this study was to use CBCTs to determine relative anchorage values of maxillary teeth by measuring and comparing the root surface area of maxillary anterior teeth to posterior teeth. The root surface area measured was the portion of the root within alveolar bone. Due to the increasingly availability and advancement of technology and software it is hoped that this study will encourage future research of orthodontic anchorage and tooth movement that can one day be tailored to an individual patient and subsequently assist with virtual treatment objectives.

**B. Specific hypothesis**

Relative anchorage values of the maxillary posterior teeth in first premolar extraction cases are larger than the relative anchorage values of the maxillary anterior teeth.

**C. Null hypothesis**

No difference in relative anchorage values between anterior and posterior teeth of the maxilla.

## III. MATERIALS AND METHODS

### A. CBCT Selection

This was a retrospective study of CBCTs from the Endodontic and Periodontic departments at the Air Force Postgraduate Dental School (AFPDS) at Joint Base San Antonio – Lackland, TX. All CBCTs were captured on an Accuitomo 170 machine with various field of views (FOV) as depicted in the following chart (Table 01).

| Voxel (mm) | FOV (mm) | Scan Mode | Small Adult | Medium Adult | Large Adult |
|---|---|---|---|---|---|
| 0.08 | 40 x 40 | 360° | 90kV/3mA | 90kV/5mA | 90kV/6mA |
| 0.125 | 60 x 60 | 360° | 90kV/3mA | 90kV/5mA | 90kV/6mA |
| 0.16 | 80 x 80 | 360° | 80kV/3mA | 80kV/5mA | 90kV/7mA |

Table 01 - Accuitomo 170 FOV and Voxel size

CBCT images meeting the inclusion criteria were evaluated to determine the feasibility of tracing the maxillary roots. The following criteria were used for inclusion of CBCTs in this study: CBCTs taken between 01 January 2012 through 31 December 2015; CBCTs with a field of view that captured the crown and roots of maxillary permanent central incisors, lateral incisors, canines, 1$^{st}$ premolars, 2$^{nd}$ premolars, 1$^{st}$ molars, and/or 2$^{nd}$ molars. The following criteria will be used for exclusion of CBCTs in this study: immature roots (roots with an open apex); roots with significant resorption; poor image quality attributed to either low resolution and/or the presence of artifacts resulting in the inability to trace the root; images obtained before 01 January 2012 or after 31 December 2015; inability to identify the type of tooth (i.e. distinguishing between a maxillary 1$^{st}$ and 2$^{nd}$ premolar if the patient had extractions in conjunction with previous orthodontic treatment; or congenitally missing); maxillary molars with more or less than three roots; teeth with significant bone loss (for this study, significant bone loss was defined as the bone level at or apical to half the distance from the CEJ to the apex of the root). From a previous study[10], it was discovered that there were a limited number of teeth that meet the inclusion criteria and the author[10] of this study, in some instances, used subjects with a single traceable tooth. In effort to increase the sample population due to the exclusion criteria, this investigation will also include subjects that may have a single traceable tooth.

**B. Measuring Root Surface Area**

CBCTs, stored as Digital Imaging and Communications in Medicine (DICOM) files, meeting the inclusion criteria were imported into Materialise Mimics (Leuven, Belgium). Materialise Mimics was used to view CBCTs in the sagittal, axial, and coronal planes (Figure 03).

Figure 03 - CBCT illustrated in Materialise Mimics

Each tooth meeting the inclusion criteria was outlined by navigating within the software and marking the circumference of the root slice-by-slice throughout all three planes of space.  The slices were then combined to provide an outline of the root surface which allowed for the creation of a three-dimensional image.  This process created a “mask” of the root surface which was assigned a color for ease of identification (Figure 04).

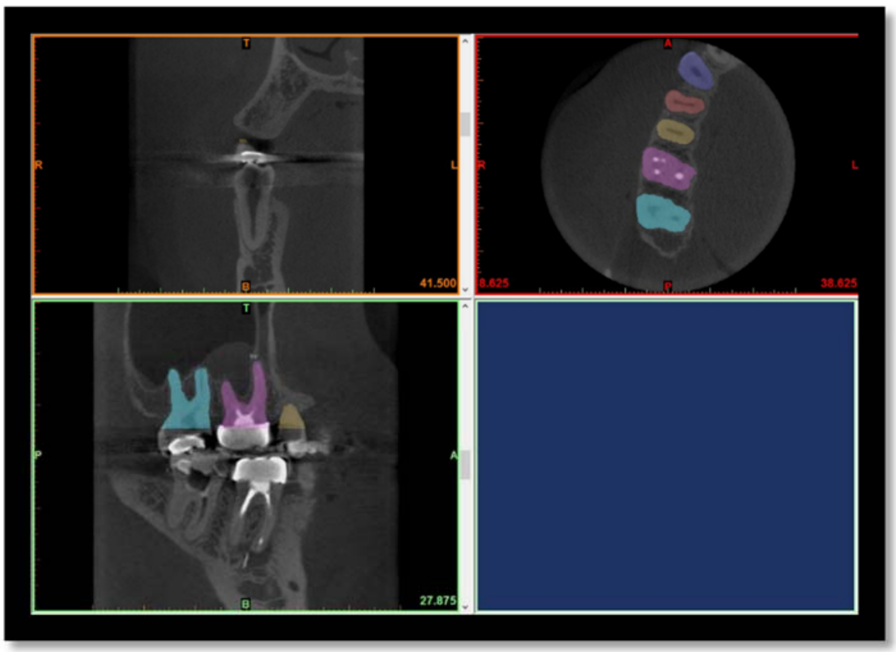



Figure 04 - Isolating teeth in Materialise Mimics

Next, the alveolar bone surrounding the roots were isolated in order to create “masks” of the bone (Figure 05).

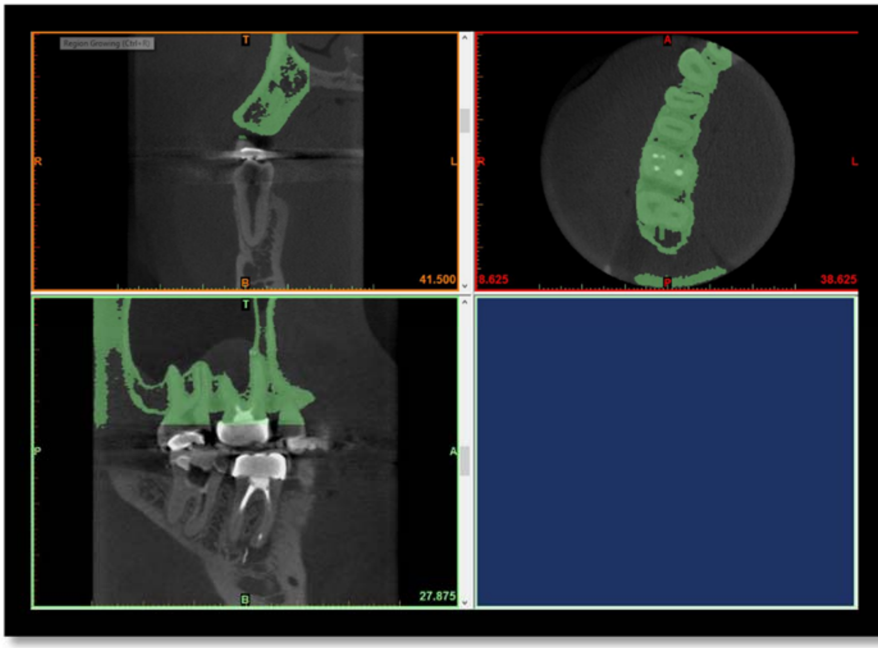



Figure 05 - Isolating bone in Materialise Mimics

The “masks” of the bone and roots were combined to create 3D models (Figure 06).

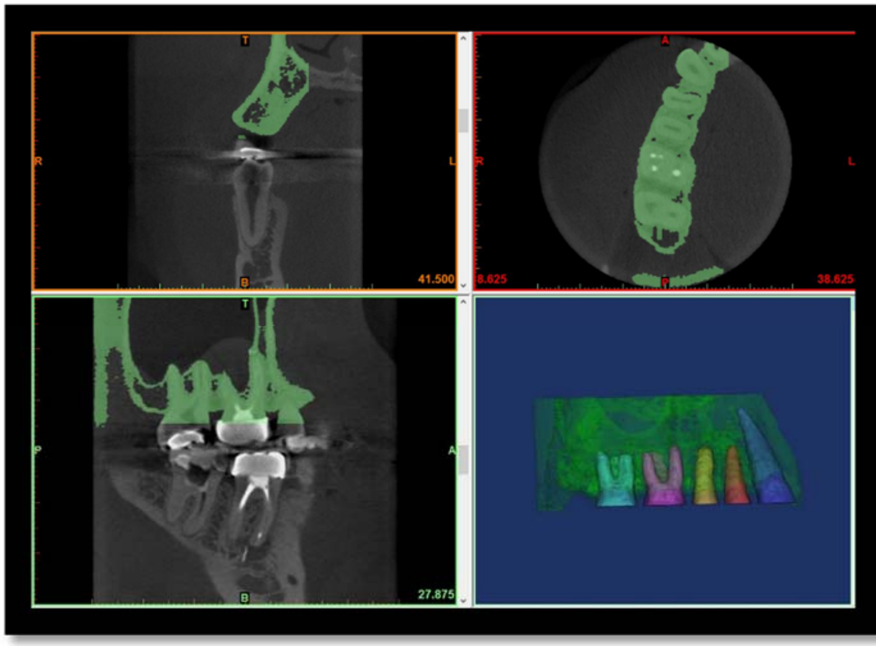



Figure 06 - Combining root and bone masks in Materialise Mimics

Teeth were then isolated from the alveolar bone, providing an unobstructed 3D image of the root surfaces (Figure 07).

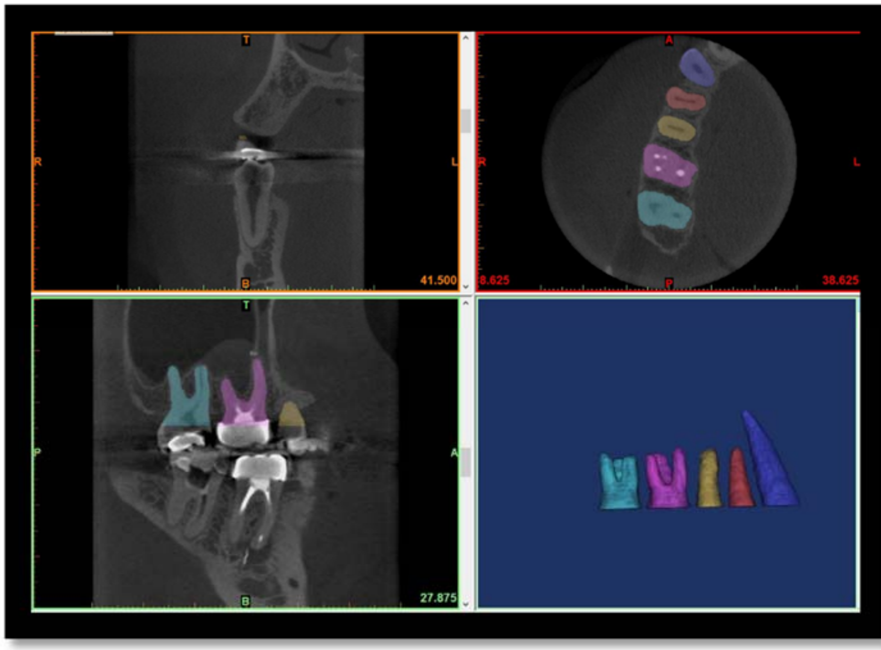



Figure 07 - Isolation of maxillary teeth in Materialise Mimics

The process utilized by Materialise Mimics to connect the various slices of root outlines resulted in a 3D image of the root with an irregular, roughened appearance (Figure 08).

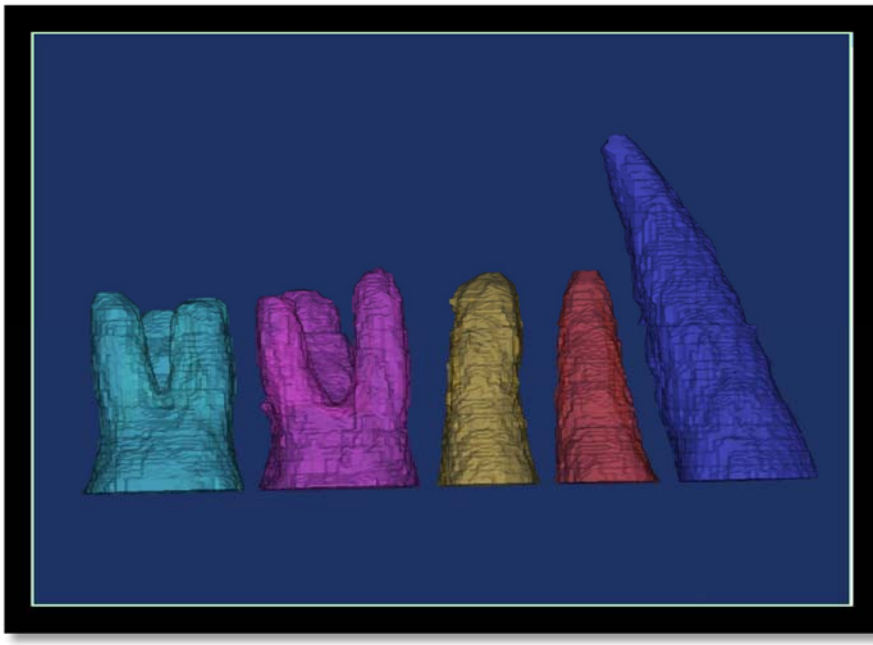


Figure 08 - Magnified maxillary root surface area displaying irregular, roughened appearance

The 3D reconstructed outlines created through Materialise Mimics were imported as a stereolithography file (STL) into Geomagic Freeform Plus (Rock Hill, SC). Geomagic's software algorithm removed the irregularities of the root surface and alveolar bone outlines using their "smooth function" embedded in the program (Figure 09).

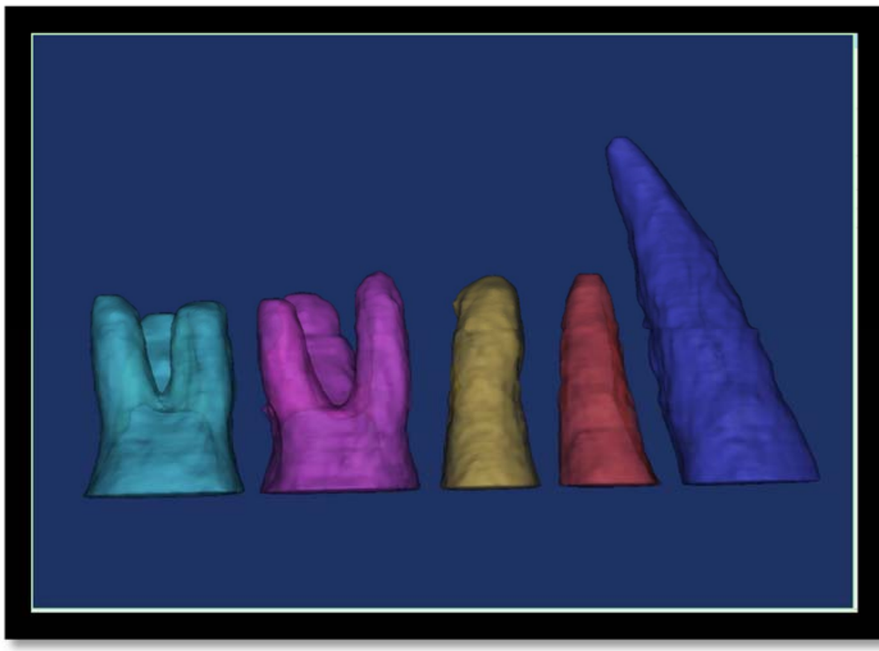


Figure 09 - Removal of irregularities from maxillary root surfaces in Materialise Mimics

Using the reconstructed smoothed images, maxillary roots were outlined at the level at which they emerged from crestal bone (Figure 10).

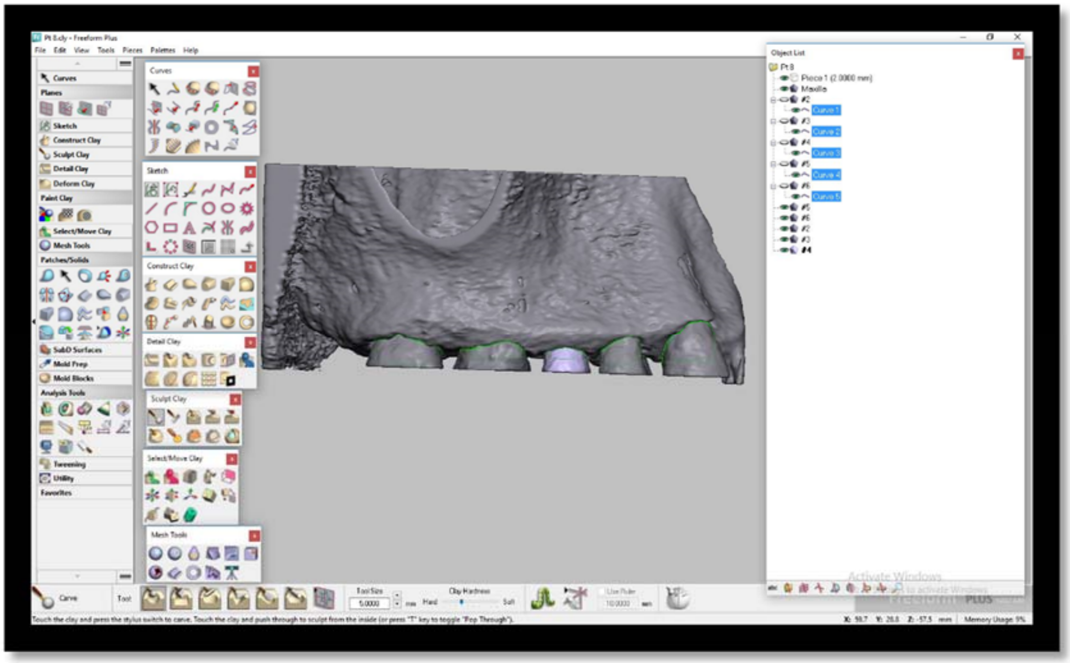


Figure 10 - Identification of root surface at level of crestal bone in Geomagic Freeform Plus

Maxillary teeth with root surfaces outlined at the level of the crestal bone were isolated from alveolar bone (Figure 11).

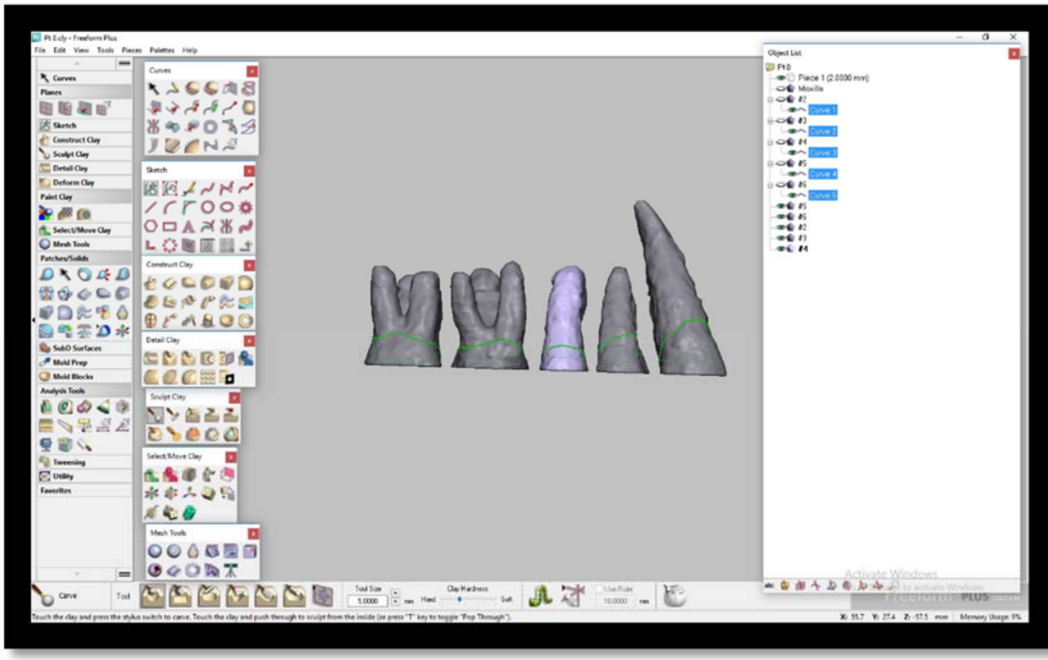


Figure 11 - Isolation of maxillary roots from alveolar bone in Geomagic Freeform Plus

Next, root surfaces below crestal bone were isolated (Figure 12).

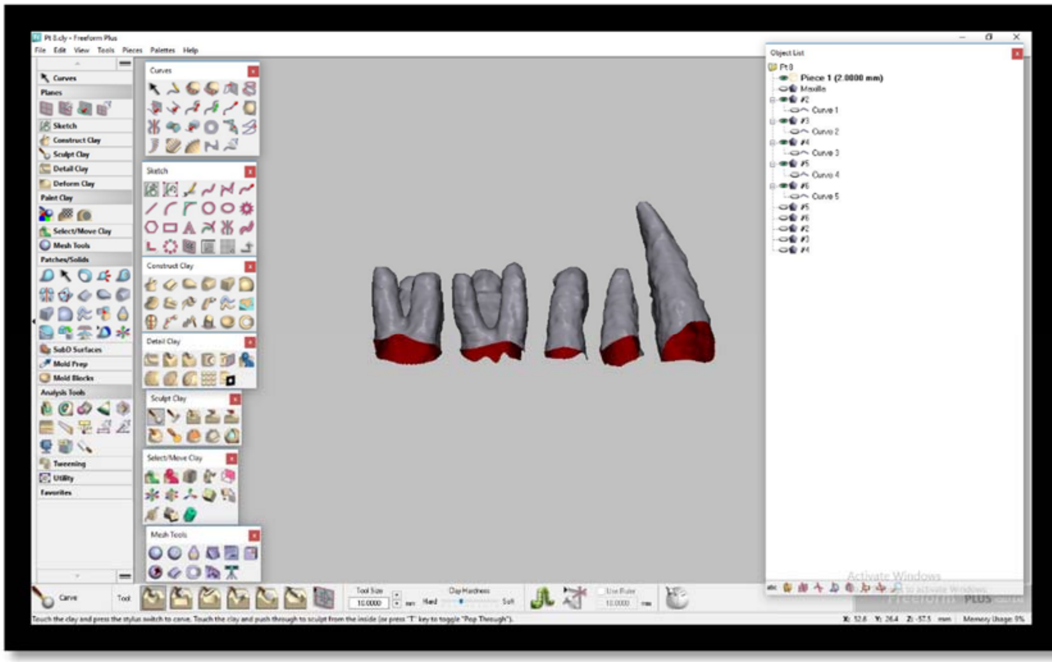


Figure 12 - Maxillary root surface below crestal bone in Geomagic Freeform Plus

To calculate relative anchorage values (i.e. root surface area below crestal bone height), the “Mass Properties” function embedded in the Geometric software was utilized to generate a measurement of root surface area in $mm^2$ (Figure 13).

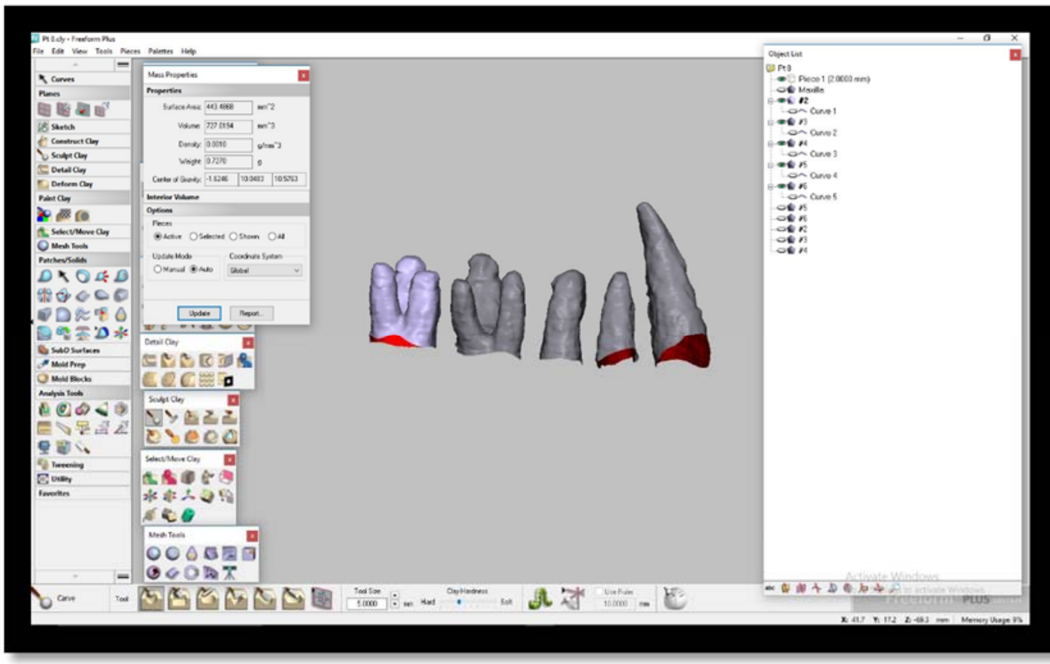



Figure 13 - Mass Properties calculation in Geomagic Freeform Plus

# IV. STATISTICAL ANALYSIS

## A. Rater reliability

Table 02 - t-test for intra-rater measurements

| Rater measurements for reliability | | | |
|---|---|---|---|
| | Initial (mm$^2$) | Second (mm$^2$) | t-test |
| 1 | 326.99 | 322.86 | 0.2070793 |
| 2 | 347.87 | 366.62 | |
| 3 | 179.6 | 179.9 | |
| 4 | 133.19 | 135.77 | |
| 5 | 280.89 | 285.34 | |
| 6 | 241.59 | 238.18 | |
| 7 | 136.13 | 138.7 | |
| 8 | 561.53 | 556.78 | |
| 9 | 378.65 | 393.93 | |
| 10 | 133.66 | 135.92 | |

Figure 14 - Bivariate Fit of Intra-rater measurements

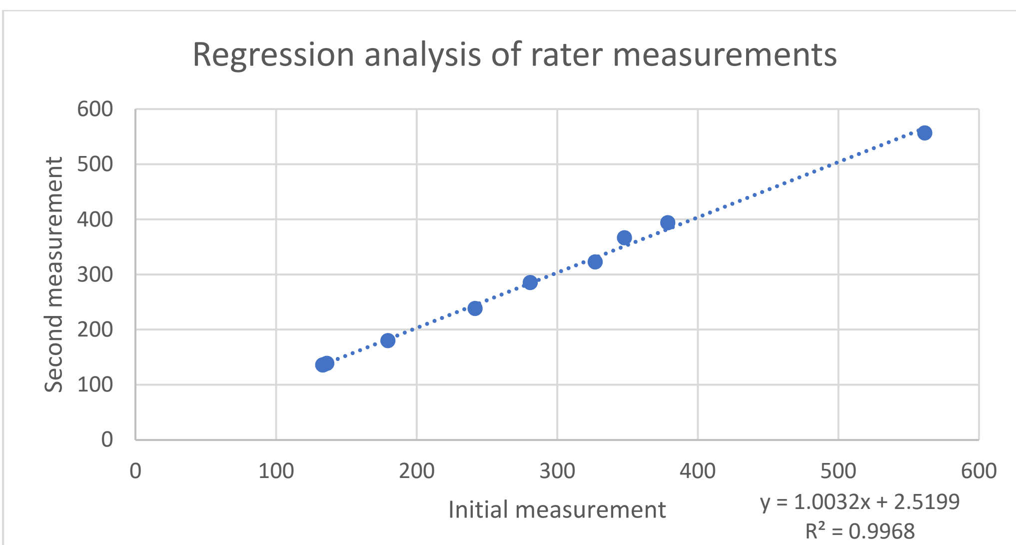


Figure 15 - Bland & Altman plot for intra-rater measurements


## B. Descriptive Statistics

Table 03 - Maxillary descriptive statistics summary

| Descriptive statistics of maxillary relative anchorage values | | | | | |
|---|---|---|---|---|---|
| Maxillary Tooth Type | Sample size | Total Surface area ($mm^2$) | Mean ($mm^2$) | Standard deviation ($mm^2$) | Range ($mm^2$) |
| Central | 12 | 1912.35 | 159.36 | 21.06 | 133-203 |
| Lateral | 12 | 1639.32 | 136.61 | 30.40 | 100-192 |
| Canine | 18 | 4012.56 | 222.92 | 53.81 | 155-359 |
| 1st Premolar | 20 | 3564.62 | 178.23 | 38.85 | 116-247 |
| 2nd Premolar | 18 | 3051.18 | 169.51 | 36.51 | 107-230 |
| 1st molar | 15 | 5544.28 | 369.62 | 66.38 | 279-477 |
| 2nd molar | 12 | 3916.78 | 326.40 | 101.11 | 176-487 |

Figure 16 - Maxillary Inter-quartile summary

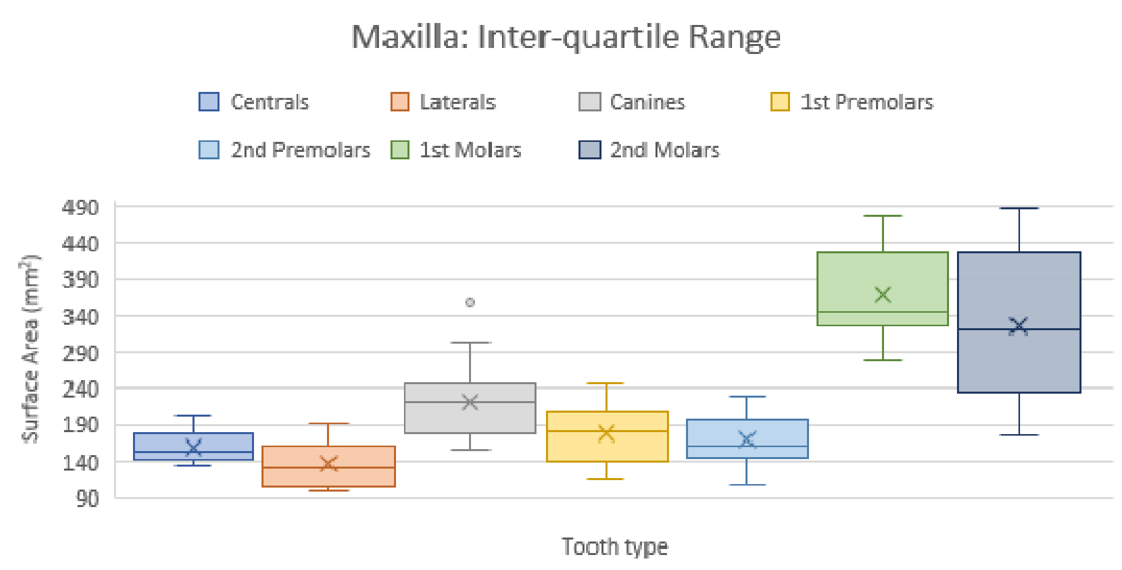
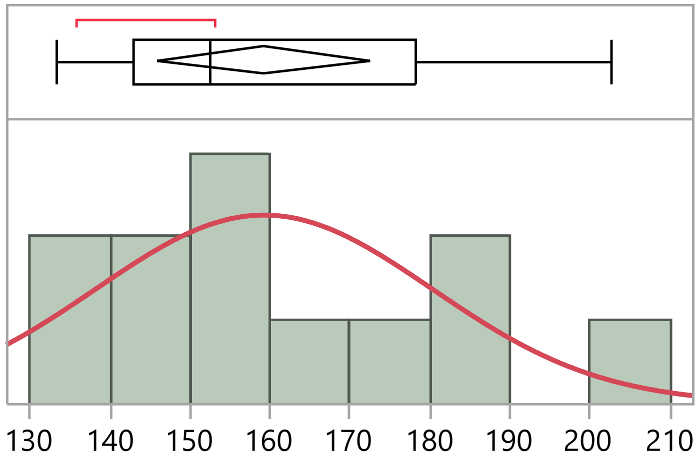



Table 04 - Maxillary skewness and kurtosis

| | Skewness | Kurtosis |
|---|---|---|
| Centrals | 0.180276 | -1.15917 |
| Laterals | 0.291338981 | -1.016520215 |
| Canine | 0.909693 | 1.035787 |
| 1st Premolars | -0.12196 | -1.10648 |
| 2nd Premolars | -0.00135 | -0.88415 |
| 1st Molars | 0.540413 | -0.90324 |
| 2nd Molars | 0.180276 | -1.15917 |

Figure 17.1 - Centrals




**Quantiles**

| | | |
|---|---|---|
| 100.0% | maximum | 202.77 |
| 99.5% | | 202.77 |
| 97.5% | | 202.77 |
| 90.0% | | 196.572 |
| 75.0% | quartile | 178.19 |
| 50.0% | median | 152.62 |
| 25.0% | quartile | 142.76 |
| 10.0% | | 133.928 |
| 2.5% | | 133.19 |
| 0.5% | | 133.19 |
| 0.0% | minimum | 133.19 |

**Summary Statistics**

| | |
|---|---|
| Mean | 159.3625 |
| Std Dev | 21.057444 |
| Std Err Mean | 6.0787604 |
| Upper 95% Mean | 172.74176 |
| Lower 95% Mean | 145.98324 |
| N | 12 |

**Fitted Normal Parameter Estimates**

| Type | Parameter | Estimate | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Location | μ | 159.3625 | 145.98324 | 172.74176 |
| Dispersion | σ | 21.057444 | 14.916991 | 35.752971 |

-2log(Likelihood) = 106.188623466193

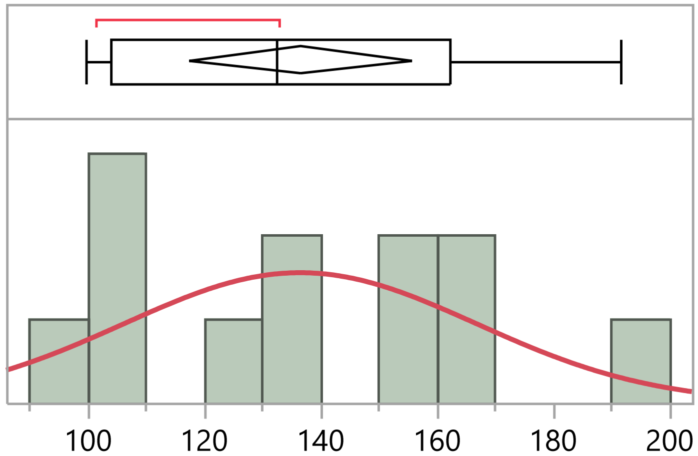
**Goodness-of-Fit Test**

Shapiro-Wilk W Test

| W | Prob<W |
|---|---|
| 0.933799 | 0.4221 |

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Figure 17.2 - Laterals




### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 191.75 |
| 99.5% | | 191.75 |
| 97.5% | | 191.75 |
| 90.0% | | 184.382 |
| 75.0% | quartile | 162.35 |
| 50.0% | median | 132.385 |
| 25.0% | quartile | 103.975 |
| 10.0% | | 100.194 |
| 2.5% | | 99.69 |
| 0.5% | | 99.69 |
| 0.0% | minimum | 99.69 |

### Summary Statistics

| | |
|---|---|
| Mean | 136.61 |
| Std Dev | 30.403352 |
| Std Err Mean | 8.7766918 |
| Upper 95% Mean | 155.92737 |
| Lower 95% Mean | 117.29263 |
| N | 12 |

### Fitted Normal Parameter Estimates

| Type | Parameter | Estimate | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Location | μ | 136.61 | 117.29263 | 155.92737 |
| Dispersion | σ | 30.403352 | 21.537587 | 51.621184 |

-2log(Likelihood) = 115.003793874144

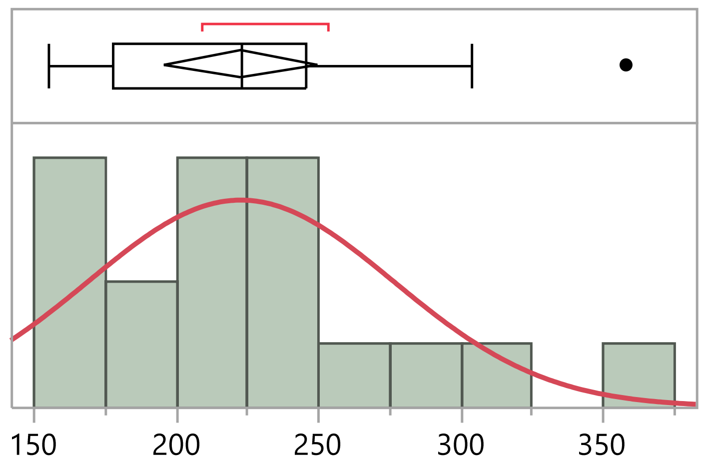
### Goodness-of-Fit Test

Shapiro-Wilk W Test

| W | Prob<W |
|---|---|
| 0.926410 | 0.3436 |

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Figure 17.3 - Canine




### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 358.67 |
| 99.5% | | 358.67 |
| 97.5% | | 358.67 |
| 90.0% | | 309.701 |
| 75.0% | quartile | 245.4 |
| 50.0% | median | 222.97 |
| 25.0% | quartile | 177.065 |
| 10.0% | | 155.459 |
| 2.5% | | 155 |
| 0.5% | | 155 |
| 0.0% | minimum | 155 |

### Summary Statistics

| | |
|---|---|
| Mean | 222.92 |
| Std Dev | 53.80703 |
| Std Err Mean | 12.682439 |
| Upper 95% Mean | 249.67761 |
| Lower 95% Mean | 196.16239 |
| N | 18 |

### Fitted Normal Parameter Estimates

| Type | Parameter | Estimate | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Location | μ | 222.92 | 196.16239 | 249.67761 |
| Dispersion | σ | 53.80703 | 40.376128 | 80.664486 |

-2log(Likelihood) = 193.55633589912

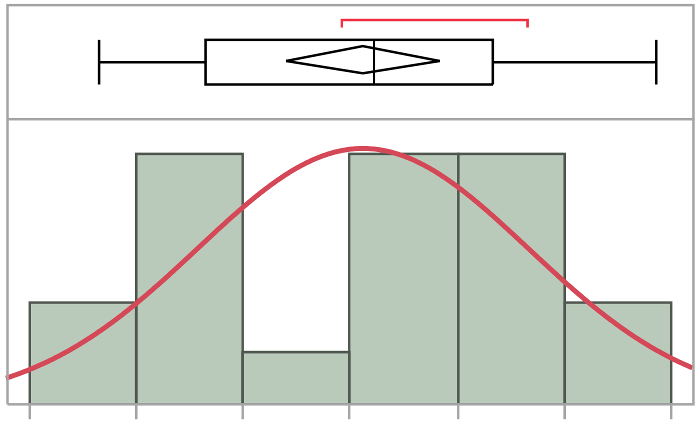
### Goodness-of-Fit Test

Shapiro-Wilk W Test

| W | Prob<W |
|---|---|
| 0.927792 | 0.1776 |

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Figure 17.4 - 1st premolar




### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 246.97 |
| 99.5% | | 246.97 |
| 97.5% | | 246.97 |
| 90.0% | | 224.959 |
| 75.0% | quartile | 208.6725 |
| 50.0% | median | 180.655 |
| 25.0% | quartile | 140.8575 |
| 10.0% | | 121.739 |
| 2.5% | | 115.89 |
| 0.5% | | 115.89 |
| 0.0% | minimum | 115.89 |

### Summary Statistics

| | |
|---|---|
| Mean | 178.231 |
| Std Dev | 38.847464 |
| Std Err Mean | 8.6865569 |
| Upper 95% Mean | 196.41217 |
| Lower 95% Mean | 160.04983 |
| N | 20 |

### Fitted Normal Parameter Estimates

| Type | Parameter | Estimate | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Location | μ | 178.231 | 160.04983 | 196.41217 |
| Dispersion | σ | 38.847464 | 29.543123 | 56.739504 |

-2log(Likelihood) = 202.143252866879

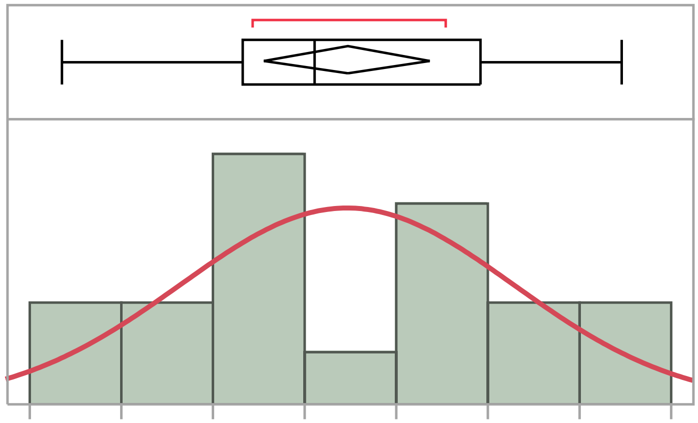
### Goodness-of-Fit Test

Shapiro-Wilk W Test

| W | Prob<W |
|---|---|
| 0.952116 | 0.4004 |

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Figure 17.5 - 2nd premolar




**Quantiles**

| | | |
|---|---|---|
| 100.0% | maximum | 229.58 |
| 99.5% | | 229.58 |
| 97.5% | | 229.58 |
| 90.0% | | 226.439 |
| 75.0% | quartile | 198.4225 |
| 50.0% | median | 162.115 |
| 25.0% | quartile | 146.1475 |
| 10.0% | | 115.412 |
| 2.5% | | 106.97 |
| 0.5% | | 106.97 |
| 0.0% | minimum | 106.97 |

**Summary Statistics**

| | |
|---|---|
| Mean | 169.51 |
| Std Dev | 36.508667 |
| Std Err Mean | 8.6051753 |
| Upper 95% Mean | 187.66533 |
| Lower 95% Mean | 151.35467 |
| N | 18 |

**Fitted Normal Parameter Estimates**

| Type | Parameter | Estimate | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Location | μ | 169.51 | 151.35467 | 187.66533 |
| Dispersion | σ | 36.508667 | 27.395651 | 54.731748 |

-2log(Likelihood) = 179.593575657851

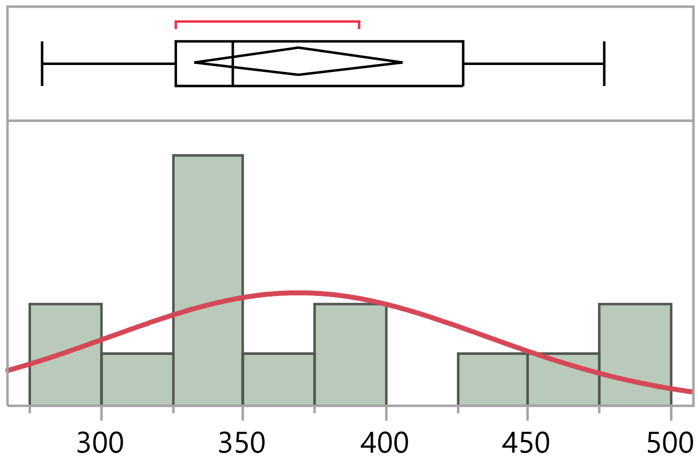
**Goodness-of-Fit Test**

Shapiro-Wilk W Test

| W | Prob<W |
|---|---|
| 0.966062 | 0.7212 |

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Figure 17.6 - 1st molar




### Quantiles

| | | |
|---|---|---|
| 100.0% | maximum | 477.12 |
| 99.5% | | 477.12 |
| 97.5% | | 477.12 |
| 90.0% | | 475.956 |
| 75.0% | quartile | 427.4 |
| 50.0% | median | 345.93 |
| 25.0% | quartile | 326.18 |
| 10.0% | | 284.184 |
| 2.5% | | 279.3 |
| 0.5% | | 279.3 |
| 0.0% | minimum | 279.3 |

### Summary Statistics

| | |
|---|---|
| Mean | 369.61867 |
| Std Dev | 66.383203 |
| Std Err Mean | 17.140069 |
| Upper 95% Mean | 406.38046 |
| Lower 95% Mean | 332.85687 |
| N | 15 |

### Fitted Normal Parameter Estimates

| Type | Parameter | Estimate | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Location | μ | 369.61867 | 332.85687 | 406.38046 |
| Dispersion | σ | 66.383203 | 48.600908 | 104.69288 |

-2log(Likelihood) = 167.431477871829

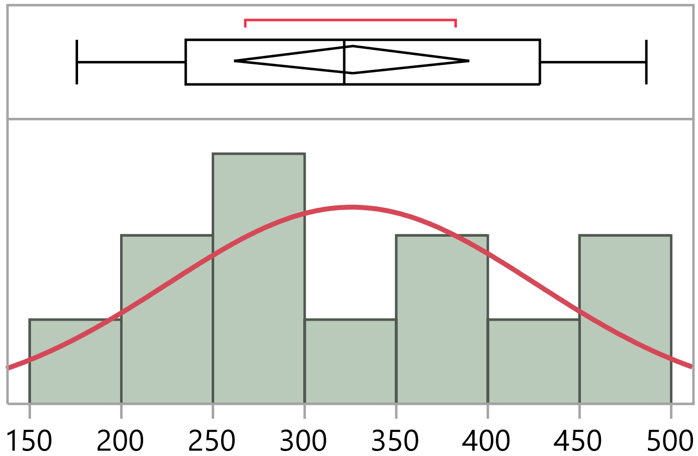
### Goodness-of-Fit Test

Shapiro-Wilk W Test

| W | Prob<W |
|---|---|
| 0.909400 | 0.1326 |

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Figure 17.7 - 2nd molar




**Quantiles**

| | | |
|---|---|---|
| 100.0% | maximum | 487.19 |
| 99.5% | | 487.19 |
| 97.5% | | 487.19 |
| 90.0% | | 476.483 |
| 75.0% | quartile | 428.4325 |
| 50.0% | median | 321.68 |
| 25.0% | quartile | 235.1125 |
| 10.0% | | 187.921 |
| 2.5% | | 175.66 |
| 0.5% | | 175.66 |
| 0.0% | minimum | 175.66 |

**Summary Statistics**

| | |
|---|---|
| Mean | 326.39833 |
| Std Dev | 101.10735 |
| Std Err Mean | 29.187177 |
| Upper 95% Mean | 390.63888 |
| Lower 95% Mean | 262.15779 |
| N | 12 |

**Fitted Normal Parameter Estimates**

| Type | Parameter | Estimate | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Location | μ | 326.39833 | 262.15779 | 390.63888 |
| Dispersion | σ | 101.10735 | 71.623955 | 171.66794 |

-2log(Likelihood) = 143.842911957233

**Goodness-of-Fit Test**

Shapiro-Wilk W Test

| W | Prob<W |
|---|---|
| 0.955489 | 0.7180 |

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

## C. Regression and ratio analysis of collected data in comparison to the Freeman study

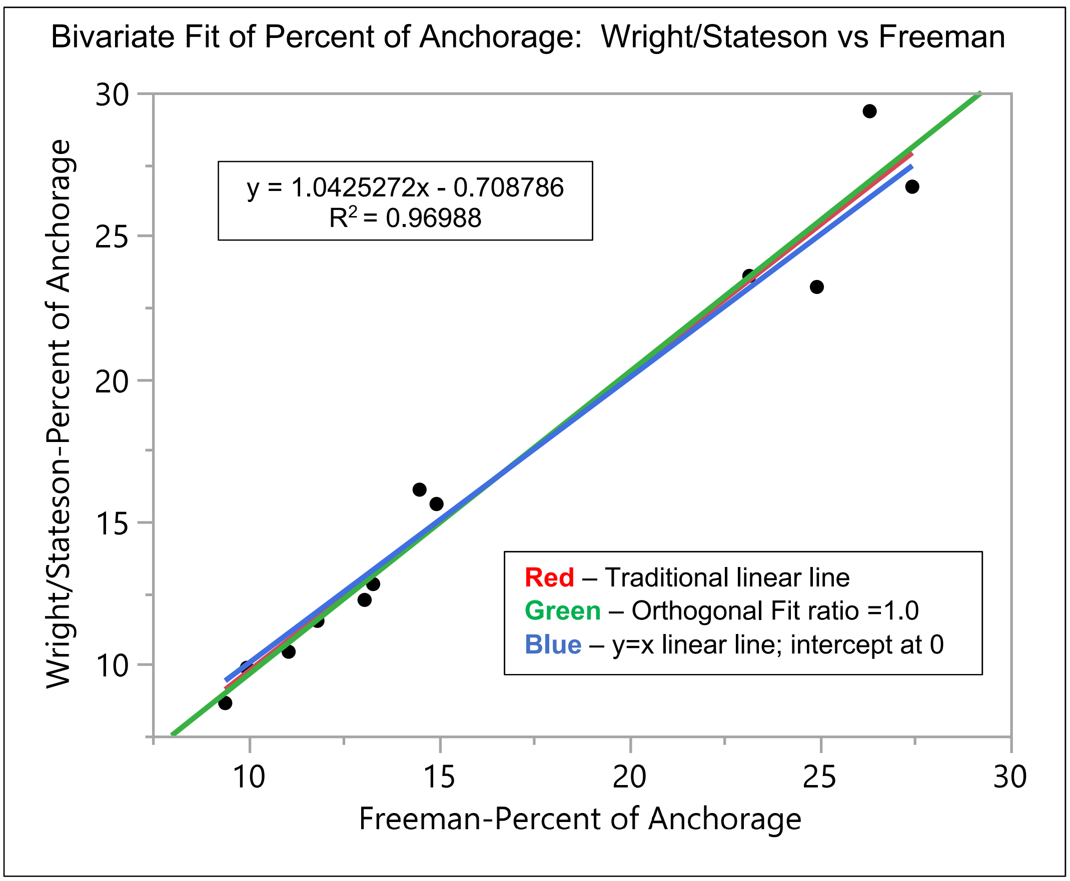
Table 05 - Freeman vs Wright/Stateson anchorage value ratios

| | Freeman – anchorage values | | Wright/Stateson – relative anchorage values | |
|---|---|---|---|---|
| | Surface Area (mm²) | Percent of Anchorage | Surface Area (mm²) | Percent of Anchorage |
| **Maxilla** | | | | |
| Centrals | 230 | 11.84 | 159.36 | 11.51 |
| Laterals | 194 | 9.98 | 136.61 | 9.87 |
| Canines | 282 | 14.51 | 222.92 | 16.10 |
| 1st premolars | n/a | n/a | n/a | n/a |
| 2nd premolars | 254 | 13.07 | 169.51 | 12.24 |
| 1st molars | 533 | 27.43 | 369.62 | 26.70 |
| 2nd molars | 450 | 23.16 | 326.40 | 23.58 |
| **Mandible** | | | | |
| Centrals | 170 | 9.42 | 120.07 | 8.64 |
| Laterals | 200 | 11.08 | 145.02 | 10.43 |
| Canines | 270 | 14.96 | 216.86 | 15.60 |
| 1st premolars | n/a | n/a | n/a | n/a |
| 2nd premolars | 240 | 13.30 | 177.93 | 12.80 |
| 1st molars | 475 | 26.32 | 407.85 | 29.34 |
| 2nd molars | 450 | 24.93 | 322.41 | 23.19 |

Table 06 - Percent of posterior anchorage

| Maxilla - percent of anchorage | | | Mandible - percent of anchorage | | |
|---|---|---|---|---|---|
| Study | Anterior (Central-canine) | Posterior ($2^{nd}$ premolar -$2^{nd}$ molar) | Study | Anterior (Central-canine) | Posterior ($2^{nd}$ premolar -$2^{nd}$ molar) |
| Freeman | 36.34% | 63.66% | Freeman | 35.46% | 64.54% |
| Stateson | 37.48% | 62.52% | Wright | 34.67% | 65.33% |
| Difference of 1.14% for posterior | | | Difference of 0.79% for posterior | | |

Figure 18 - Regression analysis of anchorage ratios from Freeman and Wright/Stateson study



## V. RESULTS

### A. Raw data

Table 07 - Raw data of maxillary teeth

| | Maxillary root surface area ($mm^2$) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Sample** | **Centrals** | **Laterals** | **Canines** | **1st Premolars** | **2nd Premolars** | **1st Molars** | **2nd Molars** |
| 01 | 133.19 | 99.69 | 155 | 115.89 | 106.97 | 279.3 | 175.66 |
| 02 | 135.65 | 101.37 | 155.51 | 121.1 | 116.35 | 287.44 | 216.53 |
| 03 | 140.64 | 102.37 | 164.18 | 127.49 | 122.64 | 312.16 | 224.29 |
| 04 | 149.12 | 108.79 | 166.58 | 132.07 | 138.67 | 326.18 | 267.58 |
| 05 | 150.36 | 127.13 | 180.56 | 138.69 | 148.64 | 326.99 | 270.19 |
| 06 | 152.09 | 132.09 | 185.66 | 147.36 | 152.7 | 334.1 | 295.49 |
| 07 | 153.15 | 132.68 | 208.44 | 148.4 | 153.84 | 336.19 | 347.87 |
| 08 | 160.89 | 154.48 | 215.96 | 173.25 | 155.97 | 345.93 | 353.73 |
| 09 | 172.19 | 157.97 | 222.47 | 177.52 | 157.54 | 374.36 | 383.26 |
| 10 | 180.19 | 163.81 | 223.47 | 179.6 | 166.69 | 380.58 | 443.49 |
| 11 | 182.11 | 167.19 | 226.58 | 181.71 | 184.31 | 390.67 | 451.5 |
| 12 | 202.77 | 191.75 | 232.48 | 195.75 | 189.23 | 427.4 | 487.19 |
| 13 | | | 235.71 | 199.47 | 190.87 | 470.68 | |
| 14 | | | 242.73 | 200.01 | 196.28 | 475.18 | |
| 15 | | | 253.41 | 203.52 | 204.85 | 477.12 | |
| 16 | | | 280.89 | 210.39 | 209.96 | | |
| 17 | | | 304.26 | 216.48 | 226.09 | | |
| 18 | | | 358.67 | 223.87 | 229.58 | | |
| 19 | | | | 225.08 | | | |
| 20 | | | | 246.97 | | | |

## B. Evaluating anterior to posterior anchorage

Table 08 - Posterior anchorage ratios excluding first premolars

| **Units in mm²** | **Freeman, 1965/7** | **Wright, 2017; Stateson, 2019** |
|---|---|---|
| Maxilla anterior (#6-11) | 1412mm² | 1037 mm² |
| Maxilla posterior (#2-4, 13-15) | 2474 mm² | 1731 mm² |
| Percent of posterior anchorage from total maxillary anchorage | 63.7% | 62.5% |
| Mandible anterior (#22-27) | 1280 mm² | 964 mm² |
| Mandible posterior (#18-20, 29-31) | 2330 mm² | 1816 mm² |
| Percent of posterior anchorage from total mandibular anchorage | 64.5% | 65.3% |

Table 09 - Posterior anchorage ratios excluding first premolars and second molars

| **Units in mm²** | **Freeman, 1965/7** | **Wright, 2017; Stateson, 2019** |
|---|---|---|
| Maxilla anterior (#6-11) | 1412 mm² | 1037 mm² |
| Maxilla posterior (#3-4, 13-14) | 1574 mm² | 1078 mm² |
| Percent of posterior anchorage from total maxilla anchorage | 52.7% | 51% |
| Mandible anterior (#22-27) | 1280 mm² | 964 mm² |
| Mandible posterior (#19-20, 29-30) | 715 mm² | 2136 mm² |
| Percent of posterior anchorage from total mandibular anchorage | 52.8% | 54.9% |

## VI. DISCUSSION

One rater was tasked to conduct all measurements with Mimics and Geometric software. To determine reliability of the rater a t-test, regression analysis, and Bland & Altman plot were conducted. Intra-class correlation coefficients (ICC) was not deemed necessary since there was only one rater performing two sets of measurements. The t-test (Table 02) resulted in a value of 0.21, suggesting no significant differences amongst the measurements. Regression analysis of intra-rater measurements (Figure 14) demonstrated tight groupings of the initial and second measurements with an $R^2$ value of 0.9968, indicating the regression model explains all the variability of the data around the mean. Bland & Altman plot (Figure 15) showed agreement amongst the measurements within a 95% confidence interval suggesting no bias. The Bland & Altman plot also demonstrated less variability of the maxillary anterior root surfaces and increase variability in the maxillary posterior teeth. Reasons for this variation can be attributed to the multi-rooted tooth structure of posterior teeth.

Initial screening of CBCTs included 440 patients, however, after following the inclusion and exclusion criteria, only 17 CBCTs were included for this investigation. Surface area, calculated in $mm^2$, for each sample is provided in Table 03 (Maxillary descriptive statistics summary). Sample size ranged from 12 (for centrals, laterals, and second molars) to 20 (1st premolars) and totaled 107 teeth that met the inclusion criteria (Refer to Table 07 - Raw data of maxillary teeth).

This study is a pilot study without either a control group or independent variable, thus, descriptive statistics were utilized for analyzing relative anchorage values. Maxillary descriptive statistics summary (Table 03) provides the following information regarding relative anchorage values: Central incisors 159 $mm^2$ with a standard deviation (std dev) of 21 $mm^2$; lateral incisors 137 $mm^2$ with a std dev of 30 $mm^2$; canines 223 $mm^2$ with a std dev of 54 $mm^2$; 1st premolars 178 $mm^2$ with a std dev of 39 $mm^2$; 2nd premolars 170 $mm^2$ with a std dev of 37 $mm^2$; 1st molars 370 $mm^2$ with a std dev of 66 $mm^2$; and 2nd molars 326 $mm^2$ with a std dev of 101 $mm^2$.

A summary of the Maxillary inter-quartile range (Figure 16) and its corresponding skewness and kurtosis (Table 04) demonstrate the quality of data obtained from this investigation. In addition, more detailed information for each maxillary tooth type (Figure 17.1-17.7) is provided. All teeth have a skewness and kertosis close to zero, all teeth had a mean that was relatively close in value to their respective median, and according the Shapiro-Wilk test, all data had a W value greater than 0.9. This information suggests robust data that appears to be normally distributed.

All data falls within the 95% Confidence Interval except for a single sample for the maxillary central (202.77 $mm^2$; Figure 17.1) and canine (358.67 $mm^2$; Figure 17.3). Reasons for these outliners can be attributed to a small sample size, a heterogeneous sample population, and/or abnormally sized roots. For example, the outliner for the maxillary canine had a size similar to the mean of the 1st and 2nd molars. In regards to homogeneous versus heterogeneous sample populations, historical studies in the orthodontic literature have been primarily on Caucasian subjects. The population of this study is the United States military and eligible beneficiaries, which is heterogeneous in nature. One study[16] demonstrated African Americans had larger surface areas of teeth than Caucasians, with an observed difference of 214.45mm$^2$.

The Freeman study measured total root surface area, i.e. root surface area below CEJ. The current study measured root surface area within alveolar bone. These values cannot be directly assessed due to the variation in measurement technique. In order to compare relative anchorage values obtained from this study and anchorage values from the Freeman study, it was necessary to calculate ratios of individual anchorage (percent of anchorage for a particular tooth to the overall anchorage of the maxilla). First premolars were not included for the ratio calculation due to the exclusion of these teeth in the original study by Freeman (Table 05). Overall ratios of anchorage values were calculated (Table 06) and demonstrated minor differences between the Freeman and Wright/Stateson values.

Raw data from the Freeman study was not available, however, raw data from the Wright study[10] was available. Ratios (Table 05) were imputed into regression analysis (Figure 18) to compare the Freeman study to the Wright/Stateson study. Regression analysis of the individual tooth ratios showed very balanced, robust similarities between the Freeman and Wright/Stateson study suggesting little to no bias.

When comparing relative anchorage values from this study (Table 09) for a 1st premolar extraction scenario, the anterior segment (centrals to canines) comprised of 1037 $mm^2$ and the posterior (2nd premolar to 1st molar) 1078 $mm^2$ and the percent of posterior anchorage was 51%. Because the ratio of the anterior to posterior is roughly equal for this scenario, reciprocal anchorage with equal movements of segments is expected. Comparing the relative anchorage values from this study to the anchorage values of the Freeman study with the same 1st premolar extraction, the anterior segment (centrals to canines) comprised 1412 $mm^2$ and the posterior (2nd premolar to 1st molar) 1574 $mm^2$ and the percent of posterior anchorage is 52.7%. The difference of the percent of posterior between these two studies for this extraction scenario was only 1.7%.

When comparing relative anchorage values from this study (Table 08) for a 1st premolar extraction scenario and reinforcing the posterior anchorage segment with addition of the 2nd molar, the anterior segment (centrals to canines) comprised of 1037 $mm^2$ and the posterior (2nd premolar to 2nd molar) 1731 $mm^2$ and the percent of posterior anchorage is 62.5%. Because the anterior segment is less than the posterior segment, greater movement of the anterior segment will occur. Comparing the relative anchorage values from this study to the anchorage values of the Freeman study with the same 1st premolar extraction and inclusion of the second molar, the anterior segment (centrals to canines) comprised 1412 $mm^2$ and the posterior (2nd premolar to 1st molar) 2474 $mm^2$ and the percent of posterior anchorage is

63.7%. The difference of the percent of posterior between these two studies for this extraction scenario was only 1.2%.

## VII. CONCLUSION

Anchorage is an important concept in orthodontics, and is relevant in treatment planning, particularly with cases involving extractions. Traditional methods of root surface measurements[8] provided the orthodontic community with anchorage values of teeth and have been referenced in orthodontic textbooks[6]. This study, along with the study by Wright[10], is unique for several reasons: Root surface measurements were performed on non-extracted teeth and anchorage was described in terms of tooth embedded in bone, which the authors (Stateson and Wright[10]) termed relative anchorage value.

This study confirms what was previously know about anchorage values, but with the added benefit of obtaining this information from non-extracted teeth. Both the Freeman values and the Stateson/Wright values agree that posterior anchorage (as a percentage of overall anchorage) is greater than anterior segments of the maxilla for a 1st premolar extraction scenario with reinforcement of anchorage to include the 2nd molars. This scenario allows for force distribution along a greater surface area of the anchor segment, thereby applying selective pressure resulting in more movement of the anterior segment compared to the posterior anchor segment. Exclusion of the second molars in a maxillary 1st premolar extraction scenario results in 50% anterior to posterior anchorage ratio, and reciprocal space closure with equal movements of the anterior and posterior segments is expected.

At present, manual measurement of root surface area if very time intensive requiring slice-by-slice outlining of each root in all three dimensions. In addition, many samples were excluded from this study due to poor image quality. Patient movement, streaking artifact and spatial resolution have the potential to limit outlining root surface area. This study used CBCTs taken from an Accuitomo obtaining highly detailed images with a voxel size as small as 0.08mm. The Accuitomo has much higher resolution than the traditional CBCTs utilized by orthodontists, such as the iCAT FLX that acquires images with a voxel size of 0.3mm. With the continual advancement in technology and improvement in software, perhaps one day CBCT imaging will allow for better quality of images that allow both identification of root surface area. Perhaps one day technology will allow for automated measurements and calculation of anchorage value of teeth.

This author believes the anchorage values described by Freeman, and later modified by Proffit, overestimate the anchorage values unlike relative anchorage values which provide a more accurate representation. Measurements from the Freeman study were from the CEJ to the apex of the root. In contrast, this study measured root surface area within bone. Orthodontic tooth movement requires interaction with the PDL. In addition, to achieve preferential tooth movement force distribution over a larger surface area of PDL for the anchorage segment is required to achieve a greater force concentration in the segment that is necessary for the desired tooth movement. We know from Gargulio[17] that biologic width has variability within the population, and on average, there is 2mm from the CEJ to the crestal bone. In addition, more adults are seeking orthodontic treatment and crestal bone loss may accompany physiologic aging. For these reasons, this study offers important information that relates to a patient's specific anchorage requirements.

In the days of Edward Angle, archwires were bent or twisted to include 1st, 2nd, and 3rd degree orders. With the introduction of preadjusted brackets, bends during leveling and aligning were eliminated, but still required for finishing and detailing. In today's market, virtual treatment software such as Insignia (Ormco, Orange, CA) offer precise templates for indirect bonding, further minimizing the need for bends during finishing and detailing. Insignia now allows the ability to utilize root form obtained through either root banks or from the patients CBCT imaging. Including additional information obtained from root anatomy, size and position in alveolar bone will allow for better clinical results with aligning clinical crowns. I believe relative anchorage values may one day allow for the tailoring of anchorage requirements for individual patients, yielding more efficient treatment. This would perhaps be achieved with custom archwires that precisely distribute force throughout the anterior and posterior segments.

Further investigations are needed to determine clinical relevance of these findings. Center of resistance is often hard to obtain clinically due to the inherent variability of the patient. Could we one day use 3D imaging and relative anchorage values to determine the precise center of resistance? Perhaps we can measure bone quality and quantity of the maxilla and mandible which can be used to determine the percent of space closure as it relates to the various elements of anchorage? Could certain tooth movements be better staged in virtual treatment algorithms? The future is promising, we are bound only by the advancements in technology.

# VIII. BIBLIOGRAPHY


1. Roberts-Harry D, Sandy J. Orthodontics. Part 9: Anchorage control and distal movement. Br Dent J 2004;196(5):255-63.
2. Baker RW, Guay AH, Peterson HW, Jr. Current concepts of anchorage management. Angle Orthod 1972;42(2):129-38.
3. Graber LW VR, Vig KW. Orthodontics: Current principles and techniques. 5th ed. Phildelphia, PA: Mosby, Inc.; 2012.
4. ER A. Treatment of malocclusion of the teeth. . Philadelphia: S.S. White Dental Manufacturing Co., 1907.
5. Angelopoulou MV, Koletsi D, Vadiakas G, Halazonetis DJ. Induced ankylosis of a primary molar for skeletal anchorage in the mandible as alternative to mini-implants. Prog Orthod 2015;16:18.
6. Proffit WR FH, Sarver DM. Contemporary orthodontics. 5th ed. St. Louis: Mosby; 2013.
7. Smith R SE. The importance of force in orthodontics: the design of cuspid retraction springs. Aust J Dent 1952(56):291-304.
8. Freeman D. Root surface area related to anchorage in the Begg technique. American Journal of Orthodontics 1967;53(2):139-40.
9. Quinn RS, Yoshikawa DK. A reassessment of force magnitude in orthodontics. Am J Orthod 1985;88(3):252-60.
10. Wright G. The use of CBCTs to determine relative anchorage values by measuring root surface areas within bone; Uniformed Services University of the Health Sciences - Airforce Postgraduate Dental School; 2017.
11. Hujoel PP. A meta-analysis of normal ranges for root surface areas of the permanent dentition. J Clin Periodontol 1994;21(4):225-9.
12. Jepsen A. Root surface measurement and a method for x-ray determination of root surface area. Acta Odontol Scand 1963;21:35-46.
13. Sherrard JF, Rossouw PE, Benson BW, Carrillo R, Buschang PH. Accuracy and reliability of tooth and root lengths measured on cone-beam computed tomographs. Am J Orthod Dentofacial Orthop 2010;137(4 Suppl):S100-8.
14. Damstra J, Fourie Z, Huddleston Slater JJ, Ren Y. Accuracy of linear measurements from cone-beam computed tomography-derived surface models of different voxel sizes. Am J Orthod Dentofacial Orthop 2010;137(1):16 e1-6; discussion 16-7.
15. Forst D, Nijjar S, Flores-Mir C, et al. Comparison of in vivo 3D cone-beam computed tomography tooth volume measurement protocols. Prog Orthod 2014;15:69.
16. Molini, N; Root surface area measurements of North American Negro and Caucasian extracted mandibular teeth; Loyola University, 1968.
17. Gargiulo, A. et al. Dimensions and relations of the dentogingival junction in humans. Am Periodontology 1961; 32:261-267.