Indirect Bonding of Orthodontic Brackets:
An evaluation of transfer accuracy and reliability

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Acknowledgements

I would like to extend my appreciation to Dr. Brent E. Larson for his guidance and support throughout the completion of this work. Also, I offer special thanks to Mike Marshall for his invaluable technical contributions to this project.

Dedication

This thesis is dedicated to my parents, Steven and Felisa Lee, my sister, Meredith, and wife, Nikki for your continual love and support.

Abstract

Background: Indirect bonding of orthodontic brackets has been viewed as a method of achieving greater accuracy and effectiveness in orthodontic treatment. Although the concept of indirect bonding has been widely studied, the accuracy of the transfer between the indirect stone model-set of the brackets to the patient's dentition has not been investigated in a clinical setting. The goal of the present study is to elicit the frequency, directional bias, and magnitude of bracket positioning errors due to this transfer.

Methods: A total of 163 brackets were initially placed on indirect stone model set-ups and scanned using a cone-beam computed tomography system to capture 3-D bracket positioning data. These brackets were then transferred to the patient's dentition and later scanned using CBCT to capture the final 3-D bracket positioning on the teeth. Virtual models of the teeth and attached brackets were constructed from the scanned data. Initial and final pairs of models were digitally superimposed. Differences in bracket positioning were measured using customized software. One-tailed t-tests were used to compare measurement data with the pre-determined acceptable ranges of +/- 0.5 mm linearly and 2.0 degrees angularly for differences in each of 6 dimensions studied.

Results: The indirect transfer of brackets resulted in accurate positioning ($\alpha = 0.05$, $P < 0.0001$). Bracket positioning along mesial-distal, buccal-lingual, and vertical axis most frequently satisfied the accuracy requirements. The indirect bonding transfer of brackets had a modest bias towards the buccal and gingival. The bracket failure (detachment) rate in this study was 9.8%.

Conclusions: The indirect bonding transfer is statistically accurate and reliable.

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Introduction:

Orthodontists continually look for new products and procedures that can simplify their practice, increase clinical effectiveness, or improve patient experience. From the advent of pre-adjusted edgewise appliances, researchers and clinicians have focused on improving the efficiency of aligning malpositioned teeth with minimal wire-bending. Pre-adjusted edgewise appliances have provided orthodontists the ability to achieve a gradual progression towards finishing, rather than an abrupt stage of wire bending as in the standard edgewise technique (McLaughlin 2003). The use of pre-adjusted bracket systems is based on the concept that ideal bracket placement will correct tooth positions in all three planes of space during treatment with placement of straight archwires (Shpack 2007). If the brackets are positioned correctly and the in-out compensations, tip, and torque built into the appliance are suited to the patient's dentition, only minimal wire bending will be required (McLaughlin 1991). In regards to efficient finishing, ideal bracket placement from the onset of treatment should be the goal for every practicing orthodontist.

The bonding of pre-adjusted orthodontic brackets to the patient's dentition is typically accomplished by either the direct method or the indirect method. The direct method involves placing the brackets directly onto the tooth surface. The indirect method involves initially placing the brackets first onto a dental cast of the patient's teeth, and later transferring the brackets to the patient's mouth using custom made trays or jigs.

Each of the methods described has its' own advantages and disadvantages. In particular, indirect bonding generally requires less clinical chair time for the orthodontist compared to direct bonding (Aguirre 1982). This is beneficial to both the patient and orthodontist, especially in a busy orthodontic practice where clinical chair time is of utmost value. In addition, others have argued that brackets can be placed more "ideally" using indirect bonding because the positioning is completed in a laboratory away from many of the clinical constraints and variables that complicate the direct bonding method such as moisture control, patient management, and/or hurried schedule, etc. The indirect method allows the orthodontist to establish bracket positioning when it is most convenient for him or her. This can be done hours, or even days before the patient arrives at the clinic for the actual placement of the braces on the teeth. Moreover, by being able to rotate the dental cast and view the teeth from all angles, the indirect method is perceived to allow more "ideal" placement on the center of the clinical crown.

In terms of utilization, Gorelick (1979) reported that only 17 percent of orthodontists used indirect bonding in their practice. Although the technique of indirect bonding has become more accepted in recent years due to advances in materials and development of new techniques, the majority of orthodontists still utilize the direct bonding method.

The drawbacks of indirect bonding include technical reliability, laboratory time, obtaining additional casts, increased costs, and possible hygiene considerations arising from excess adhesive (Wendl 2008). Another potential drawback of indirect bonding is that the precise positioning of the brackets on the stone model cannot be reliably transferred to the patient’s dentition. Errors in positioning may occur from the transfer of the brackets from the stone models to the patients’ teeth. For example, it is conceivable that contaminants and/or soft tissue interferences could affect the transfer in a typical orthodontic patient. Also, the thickness of the bonding material applied between the brackets and teeth during the clinical bonding procedure can vary and thus have a potential effect on final bracket positioning. Finally, the potential for errors in tray fabrication or clinical technique chair-side during the bonding procedure should not be overlooked.

The uncertainties inherent in the transfer could present a problem for clinicians using the indirect method due to the fact that bracket positioning has a direct influence on both the magnitude and direction of tooth movement. Improperly positioned brackets lead to inefficiencies in initial bracket leveling and alignment and, ultimately, longer treatment times. This is especially true when the clinician assumes that each bracket has been transferred precisely as originally placed on the stone or digital models. When malpositioned brackets are later recognized by the clinician, they must either be repositioned or archwire adjustments need to be made, which often negate the efficiencies gained by bonding indirectly at the onset of treatment. This is especially true with the use of customized appliances that are fabricated specifically for each patient. These appliances are placed using indirect bonding methods because the digitally generated brackets and wires are built for precise placement on an exact location on the tooth surface. If there is error in the indirect bonding transfer, the appliances will not be placed exactly as was engineered and planned by the practitioner, leading to reduced effectiveness of the appliance.

It is valuable to test the accuracy and reliability of the transfer of bracket positioning between dental cast and the patients' teeth because of the clinical impact malpositioned brackets have on the efficiency of orthodontic treatment. By measuring the bracket positions on both the dental casts and on their corresponding teeth, any significant discrepancies created in the transfer may be illuminated. It is important to evaluate the bracket position in all three linear and three rotational dimensions (or axes); occlusal-gingival, mesio-distal, facial-lingual, as well as bracket slot angulation, tip, and torque. These 6 sets of coordinates are often referred to as six-degress of freedom when describing the position of a free body in space. If no appreciable differences exist, the study may support the idea that indirect bonding is a valid and reliable method to attach orthodontic appliances to teeth as intended by the clinician. However, if there are measurable differences, it would be valuable to identify how the errors of the transfer are patterned and, subsequently, how the technique of indirect bonding may be modified to mitigate those errors.

In addition to testing accuracy and reliability in the present study, the author considered three particular assumptions about indirect bonding transfer errors. First, the author assumes that bracket positioning errors for indirect bonding occur more frequently on posterior teeth rather than on anterior teeth because of the greater difficulty in access posteriorly. Second, the author assumes that most vertical positioning errors in the indirect bonding method would occur more frequently towards the occlusal direction because it is seemingly more likely for the clinician to incompletely seat the transfer tray rather than “over-seat” the tray. Third, the author assumes that due to additional adhesive being applied to the brackets and teeth during the clinical bonding procedure, buccal-lingual positioning errors would occur more frequently towards the buccal. These unknown features of the indirect bonding method require further investigation.

Review of Current Literature:

Indirect bonding has been studied widely in orthodontic literature over the past several decades. Most of the studies that have been conducted have attempted to compare indirect bonding to direct bonding in terms of bond failures, bond strengths, clinical efficiencies, as well as accuracy of placement.

Recent studies have indicated that there is no significant difference in the rate of bracket failure (detachment) when comparing direct and indirect bonding (Aguirre 1982, Deahl 2007, Bozelli 2013, Swetha 2011).

In regards to placement accuracy, most studies have made their comparisons based on how well the method was able to achieve bracket placement relative to a pre-determined “ideal”. “Ideal” bracket placement was typically characterized as being the center of the clinical crown as prescribed by many pre-adjusted appliances. Studies then used this "ideal" as the standard by which to compare bracket positioning produced by either direct or indirect methods. The majority of previous investigators have used photographic methods in measuring the differences in bracket positioning from the ideal (Aguirre 1982, Koo 1999). These have mostly been in vitro studies.

A 1982 study by Aguirre et al. found that neither the direct nor indirect method was 100 percent accurate in regards to linear or angular placement in comparison to an ideal. In contrast, vertical bracket placement showed no statistically significant differences when compared to the ideal placement. The only exceptions were the maxillary canines, where the indirect method placed the bracket significantly closer to ideal and the mandibular second premolars where the direct-bonded brackets were placed closer to ideal. Angular bracket placement was statistically different on the maxillary and mandibular canines, with the indirect bonds being more accurate.

Aguirre et al. (1982) also reported that the time needed to complete the indirect bonding procedure, including laboratory time, was significantly longer than the time necessary to complete the direct bonding procedure. When only considering clinical time needed, the indirect method was significantly less time-consuming than the direct technique.

In 2011, Israel compared traditional (direct) and computer-aided (indirect) bracket placement by measuring the quality of intra-arch dental alignment at the end of simulated orthodontic treatment using artificial teeth in oven-set clay. Using the American Board of Orthodontics objective grading system (OGS), the post-treatment alignment of both direct and indirect placed brackets was evaluated. No significant differences were found in total OGS scores between the two methods. The indirect method produced a wider range of OGS scores (suggesting lower level of reliability) and was significantly less successful at achieving proper alignment and buccolingual inclination of the upper first premolars and less successful at properly angulating the lower lateral incisors. However, the indirect bonding method was significantly better at aligning the marginal ridges of teeth in the upper posterior segment than the direct method.

In 2004, Hodge and Hodge used a photographic method to evaluate the accuracy of direct and indirect bracket placement. Their study involved measurements of bracket positioning taken from photographic tracings of both a pre-bond stone model and a post-bond stone model of the patients teeth. The study found no difference between mean bracket placement errors for direct or indirect methods. The range of error in the three dimensions assessed was greater for the direct than for the indirect method. This was particularly true for vertical discrepancies where the range of error for the direct method was 1.81 mm versus 0.27 mm for the indirect method. Directly bonded brackets tended to be placed more gingivally than the ideal position.

In 2007, Deahl suggested that a shortcoming of previous research comparing the methods is that most are laboratory studies. Most variables that have been studied are surrogate measures for orthodontic success. True endpoints would measure variables that provide tangible patient benefit. Therefore, a practice-based comparison of direct and indirect bonding was completed in 2007. The study found no difference in the bond failure rates, total treatment times, and numbers of appointments between direct and indirect bonding for patients treated in private orthodontic practices.

These previous studies have compared direct and indirect bonding methods in terms of treatment duration, bond strength, bond failures, clinical/lab time cost, as well as bracket positioning on the tooth crown in comparison to an ideal. Previous investigators have used 2-D photographic methods in measuring bracket positioning in vitro (Aguirre 1982, Koo 1999). Throughout history, 2-D images of 3-D structures have been used widely in orthodontics with cephalometric and panoramic radiographs as well as clinical photography. Today, however, 3-D imaging options, such as CBCT and digital intra-oral scanners, offer a more precise and valuable instrument from which to study the 3-D structures we are interested in as practitioners. 3-D imaging and superimposition are appropriate tools to study bracket positioning.

Recently, in 2008, Wendl used 3-D image superimposition to measure transfer discrepancies on three axes in an *in vitro* transfer study (Wendl 2008). Wendl measured differences in bracket position from initial working models to a final plaster model after the indirect transfer. The measurement showed a mean deviation of 0.15 mm in the x-axis (mesial-distal), 0.17 in the y-axis (buccal-lingual), and 0.19 mm along the z-axis (vertical). No measurements of tip, rotation, or torque were made in this study.

However, there is a lack of evidence in the literature that evaluates the transfer of bracket positioning from stone models to the tooth *in vivo*.

Specific Aims of Present Work:

The general aim of this study is to validate the positional accuracy and reliability of an indirect bonding technique for orthodontic brackets *in vivo*.

Data collected in this study will be used to answer this clinically relevant question in three specific ways. First, the accuracy of bracket placement will be examined by how often the bracket is positioned within a predetermined range of +/- 0.5 mm linearly and 2.0 degrees angularly. Secondly, directional biases within the indirect bonding process will be uncovered by examining how often errors occur in either direction along each of the six axes. Finally, the incidence and location of complete bonding failures (detachments) will be examined to identify potential technique complications relevant to the indirect bonding process.

Hypothesis:

The hypothesis being tested in this study is that there is a difference (greater than or equal to 0.5 mm linearly, or 2° rotationally) in bracket positioning between the transfer casts and the teeth. The alternative hypothesis is that there is no measurable difference (less than 0.5 mm linearly, or 2° rotationally) in the bracket positioning.

Methods:

Sample Size and Selection:

This prospective study was conducted in a clinical setting with eight subjects, six female and two male. Each subject had up to 28 brackets which were measured as described above. The brackets were placed in up to four quadrant trays of up to seven brackets each for each subject. The total number of brackets bonded was 163. Some of the brackets that were bonded were not included in the final data for the following reasons: bond failures, repositioning as directed by the treating orthodontist during treatment, and software errors. A total of 28 brackets were discarded of the study. Therefore, the total number of 135 brackets were measured and included in the data set. The bracket failure rate was calculated by comparing the number of failed brackets, 16, to the number of brackets bonded, 163.

The subjects were selected from the general new patient pool at the Graduate orthodontic clinic at the University of Minnesota School of Dentistry. It is important to note that treatment methods and outcomes were not be affected by participation in this study. Data for the present study was collected from components of the treatment process that were available regardless of participation in the study. All subjects had their orthodontic brackets placed indirectly and were treated with Suresmile® software and digitally fabricated archwires. The CBCT patient scan data used in this study had been acquired to generate therapeutic models as part of the Suresmile® treatment process. The subjects received no additional radiation exposure beyond which they would otherwise have as part of the Suresmile® related orthodontic care. The present study was approved by the University of Minnesota Institutional Review Board (Study number 1109E04701).

Fabrication of Stone Cast Indirect Set-Up:

Each subject had alginate impressions taken of upper and lower dentition. The impressions were poured with green die stone (Modern Materials Die Keen, Hanau, Germany) to fabricate dental casts. Separator fluid was applied to the casts and allowed to dry. Edgewise orthodontic brackets were then positioned on the stone casts with Transbond XT light cure adhesive (3M Unitek, Saint Paul, MN, USA) applied to the bracket base. The brackets were positioned at the center of the clinical crown of each tooth. The brackets were positioned by the treating orthodontist. Various bracket systems and slot sizes were used depending on the preference of the treating orthodontist. Once all of the brackets were placed, the dental casts were placed in a light box for five minutes to cure the composite. After curing, the casts were ready to be scanned to capture the initial bracket position data set. Figure 1 displays the stone models after bracket positioning.

Figure 1: Stone Cast Indirect Set-Up

Scanning Stone Cast Initial Bracket Positions:

The stone casts were scanned using i-CAT (Imaging Sciences International, LLC, Hatfield, PA, USA) cone beam computed tomography to capture the 3-D bracket positioning data. Two thicknesses of dental wax were used to separate the arches during the scan so that all surfaces could be clearly captured. The volumetric data for both the brackets as well as their position on stone teeth were captured. Later, identical i-CAT settings were used for the intra-oral scans. The settings displayed in Table 1 were used for both scans. Figure 2 shows a 2-D reconstruction of the initial stone model scan.

Table 1: i-CAT Settings

Size of Reconstructed Volume	Diameter: 16 centimeters / Height: 8 centimeters
Resolution (Voxel Size)	0.2 mm
Scan Time	14.7 seconds
MAs	20.2
KVP	120

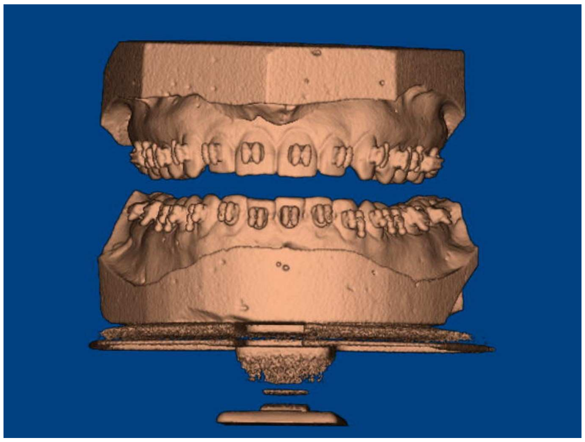
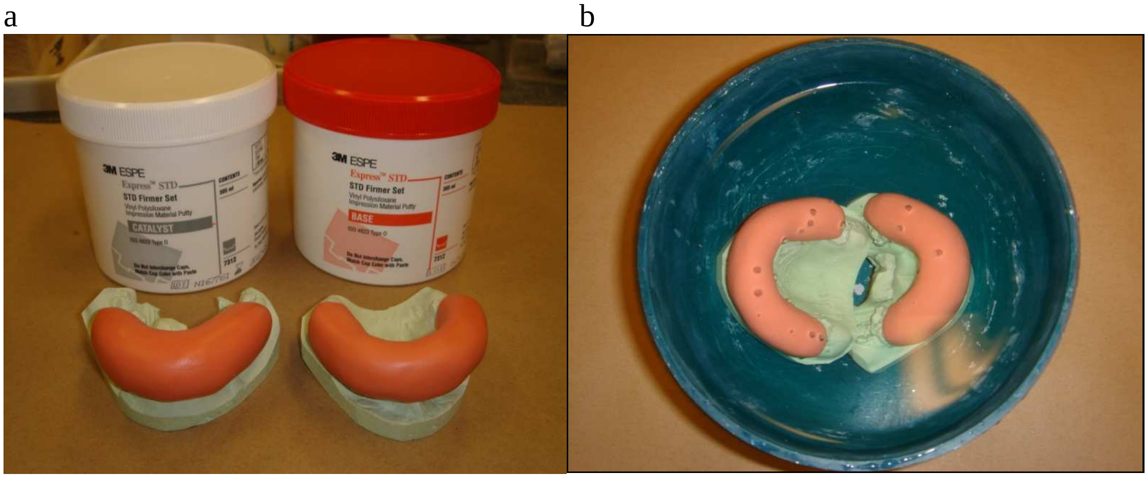


Figure 2: 2-D Reconstruction of Stone Model Scan to Capture Initial Bracket Position

Fabrication of Indirect Transfer Trays:

After the scan, vinyl polysiloxane (VPS) putty (3M ESPE Express STD Firmer set, Saint Paul, MN, USA) was mixed and applied over the dental cast teeth and brackets. The models and putty were soaked in warm water for 20 minutes. The models were then removed from the water bath and the putty was carefully removed. As the putty is removed, the brackets detach from the cast and stayed embedded in the putty matrix. The putty matrix trays were then placed back into the light box for an additional five minutes to complete the curing of composite on the bracket bases. The trays were then trimmed and sectioned at the midline into quadrants to allow for efficient intraoral placement. An alcohol wipe was used to clean debris from the base of composite and interior of the trays. All trays were fabricated by a single operator to ensure appropriate control. Figure 3 (a-d) displays the fabrication of the indirect bonding transfer trays.

a b



c d

Figure 3: Fabrication of Indirect Transfer Trays

Clinical Bonding Procedure:

Once the patient was seated, the teeth to be bonded were polished with fluoride-free pumice, rinsed with water, and dried thoroughly with oil and moisture-free air. Isolation techniques were employed to maintain a dry environment. The teeth were then etched with 37% phosphoric acid gel for 60 seconds, rinsed copiously with water, and dried until the enamel surface appeared frosted. An acid-base composite sealant (Maxcure®, Reliance Orthodontic Products, Itasca, IL, USA) was mixed and applied to the facial surface of each tooth as well as to the composite on the bracket base. The putty transfer trays were then inserted and completely seated over the teeth, one quadrant at a time, and held manually with firm finger pressure for two minutes. The trays were then left seated an additional eight minutes to allow complete curing of the sealant. The trays were then carefully removed from the teeth. The brackets were subsequently inspected to ensure successful bonding and excess cement was removed around the brackets with a handscaler. Any unsuccessful bonds were discarded from the study as these were re-bonded directly without the use of the transfer trays. Unsuccessful bonds and intentionally removed brackets were also recorded and reported in the results. Four different orthodontic residents were involved in the clinical bonding procedures on the eight patients selected for this study. Each clinician used the same bonding protocol as outlined above.

Scanning Final Bonded Bracket Positions In-Vivo:

The subjects' dentition was later scanned with i-CAT using the settings listed in Table 2. The timing of the i-CAT scan of the dentition was variable and was determined by the treating orthodontist. The scan captured the exact location of the brackets as they were bonded to the teeth. The resulting 3-D volume of the dentition and the bracket positioning was used to fabricate the Suresmile® therapeutic model. The data contained in this volume was used as the comparison to the indirect set-up data captured from the dental casts in the first scan.

Superimposition of Digitized Models:

Suresmile® proprietary software (Orametrix, Richardson, TX, USA) was used to create 3-D virtual surface models from both CBCT data volumes. Two digital models for each patient were created. The first represented the stone cast set-up. The second represented the patients' actual dentition with brackets attached. Each tooth/bracket pair was digitally sectioned out of the data set so that each was modeled as an independent unit.

The tooth and bracket pairs were superimposed using a customized tool developed for use within eModel digital 3-D software (Geodigm, Falcon Heights, MN, USA) called "bracket compare software". Each pair of teeth was superimposed using a best-fit method that achieved an adequate surface match. After the teeth surfaces were overlayed, the displacement in bracket positioning that occurred during the indirect bonding procedure could be accurately and reliably measured. The bracket compare software provided functionality to:

1.) Load .STL files that describe two similar teeth with brackets bonded to each of those teeth.

2.) Manually orient the teeth such that:

- Bracket slots are approximately parallel to the world X axis
- Occlusal tooth surfaces face toward world Z+
- Facial tooth surfaces face toward world Y-

3.) Manually select and delete tooth anatomy that might negatively influence automated best-fit alignment.

4.) Manually choose 8 datums that are used to create a coordinate system relative to the bracket slot. These datums are:

-Slot Base: two datums at the base/bottom of a slot (one on the mesial and the distal)

-Slot Bottom: two datums on the gingival surfaces of a slot (one on the mesial and the distal)

- Slot Y: two datums on a gingival surface of a slot that define a vector approx. parallel to Y
- Slot Edges: two datums whose mid-point describes the world X coordinate of the slot

5.) Automatically define a coordinate system for the slot based upon the chosen datums and then align the tooth such that the slot coordinate system coincides with the world coordinate system.

6.) Automatically apply an Iterative Closest Points (ICP) algorithm to best-fit the comparison (moveable) tooth to the reference (fixed) tooth. The slot coordinate system associated with the moveable tooth exactly follows the moveable tooth as it is repositioned during this ICP best-fit process.

7.) Manually refine the alignment of the comparison tooth to the reference tooth should this be necessary following the ICP best-fit.

8.) Automatically compare the comparison slot coordinate system to the reference slot coordinate system and record the differences between these two coordinate systems in a report file.

Six differences are reported:

M-D: Mesial-Distal translation difference (mm)

B-L: Buccal-Lingual translation difference (mm)

Vertical: Occlusal/Vertical translation difference (mm)

Torque: Torque angular difference (degrees)

Tip: Tip angular difference (degrees)

Rotation: Rotation angular difference (degrees)

These values are computed using the following formulas:

M-D: (Comparison Origin World X Coordinate) - (Reference Origin World X Coordinate)

B-L: (Comparison Origin World Y Coordinate) - (Reference Origin World Y Coordinate)

Vertical: (Comparison Origin World Z Coordinate) - (Reference Origin World Z Coordinate)

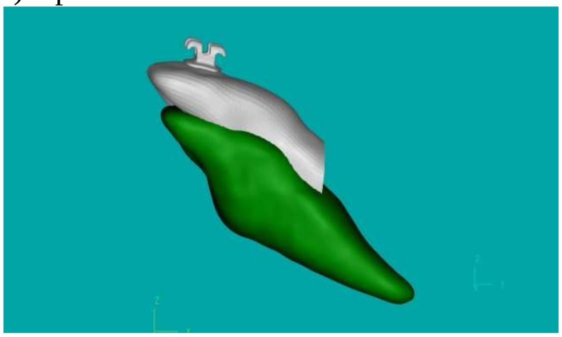
Torque: (Comparison Y Axis Rise Angle) - (Reference Y Axis Rise Angle)

Tip: (Comparison X Axis Rise Angle) - (Reference X Axis Rise Angle)

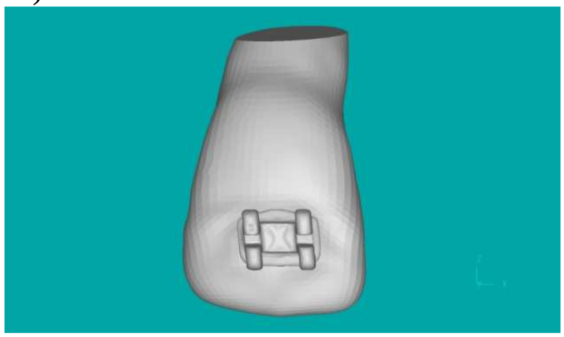
Rotation: (Comparison Y Axis RZ Angle) - (Reference Y Axis RZ Angle)

"Rise Angle" is defined as the angle that is formed between an axis and the World X-Y plane. An axis that radiates with increasing World Z coordinate values is defined as having a positive Rise Angle. An axis that radiates with decreasing World Z coordinate values is defined as having a negative Rise Angle. "RZ Angle" is defined as the angle formed between an axis and the World X axis after both have been projected onto the World X-Y plane. Figure 4 (a-w) displays screen-shots of the bracket comparison software.

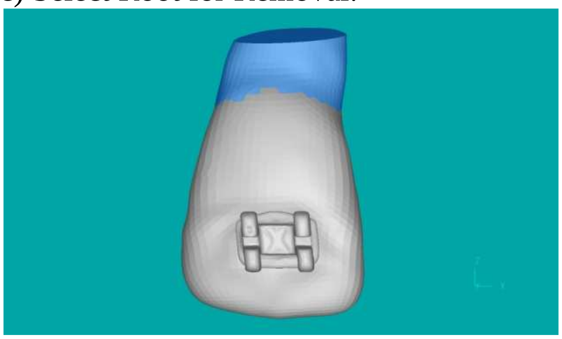
a) Open File:



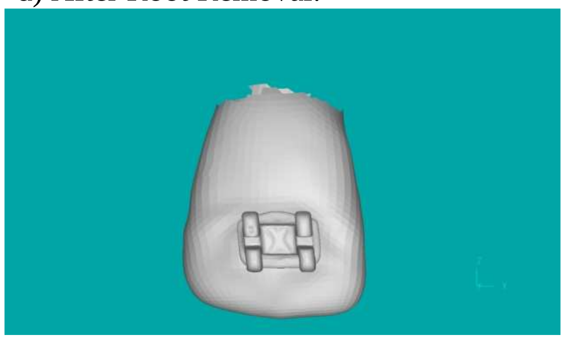
b) Orient Reference Tooth:



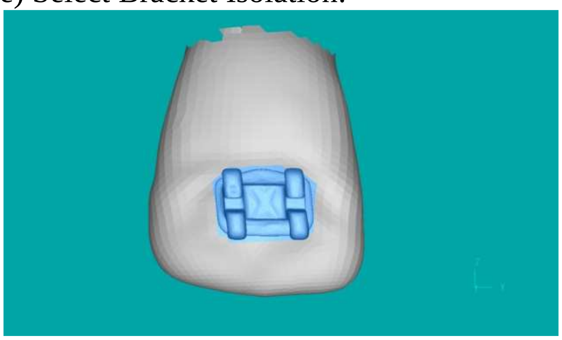
c) Select Root for Removal:



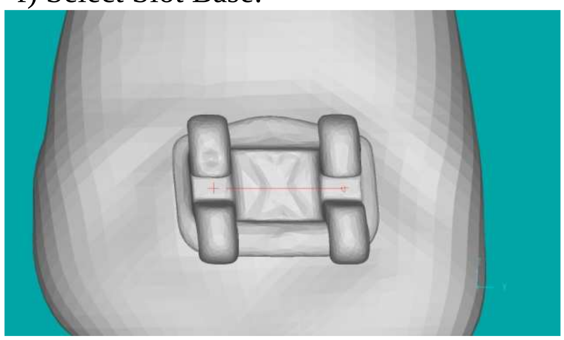
d) After Root Removal:



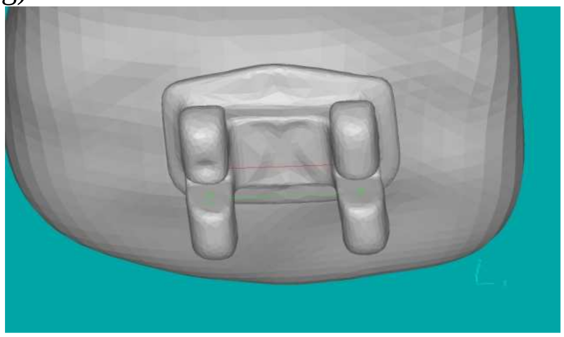
e) Select Bracket Isolation:



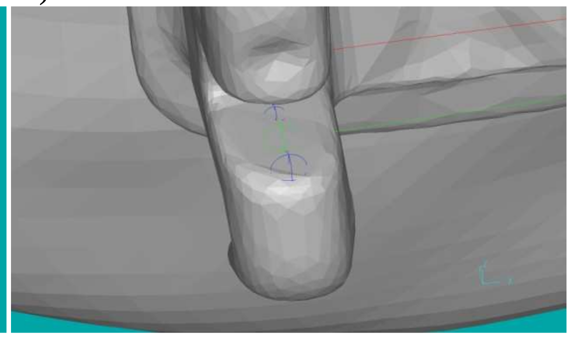
f) Select Slot Base:



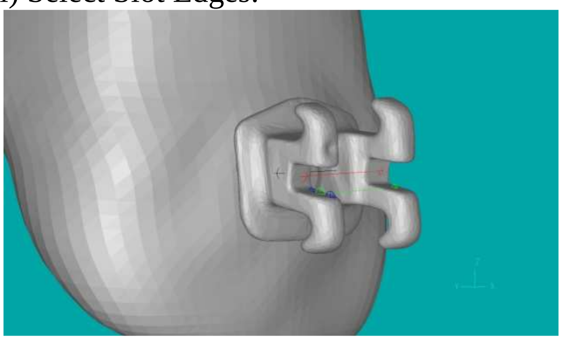
g) Select Slot Bottom:



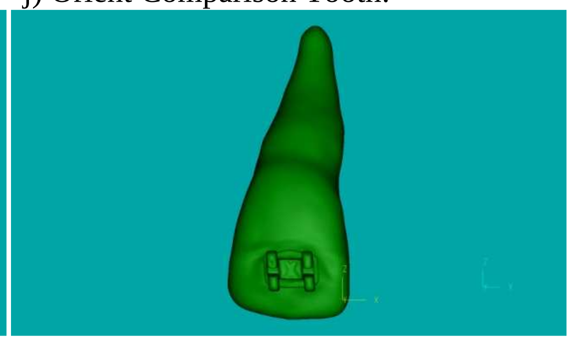
h) Select Slot Y:



i) Select Slot Edges:

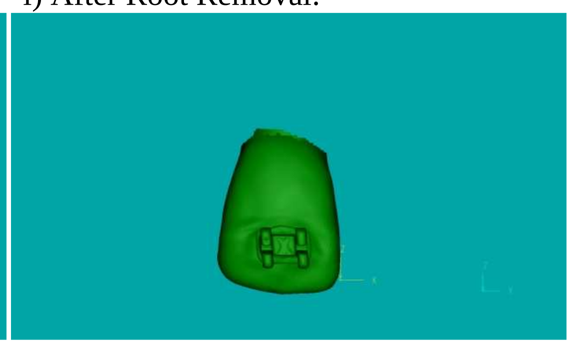


j) Orient Comparison Tooth:

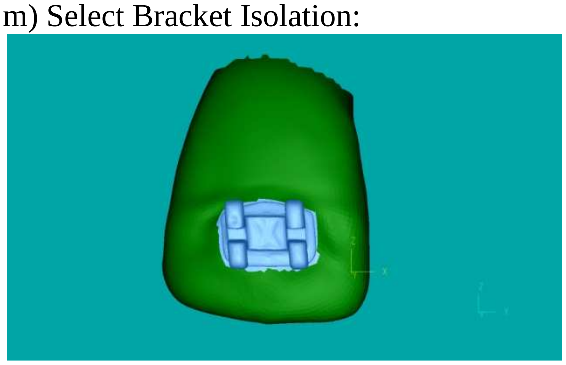


k) Select Root for Removal:

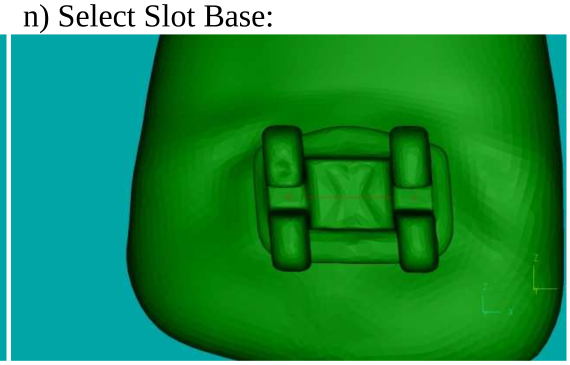
l) After Root Removal:



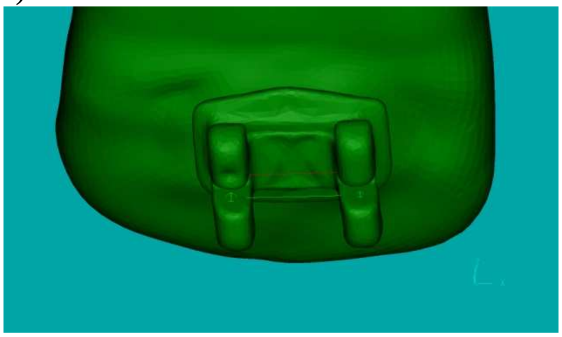
m) Select Bracket Isolation:



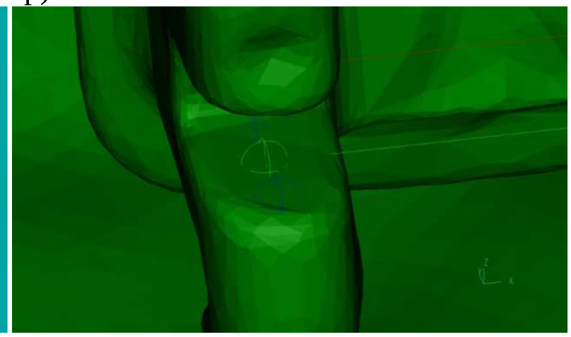
n) Select Slot Base:



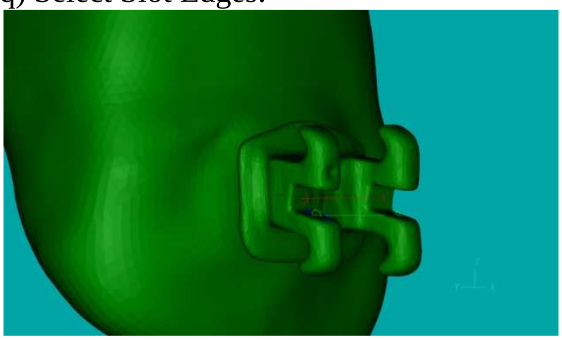
o) Select Slot Bottom:



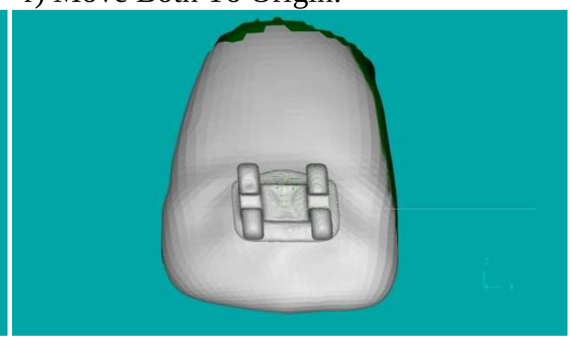
p) Select Slot Y:



q) Select Slot Edges:

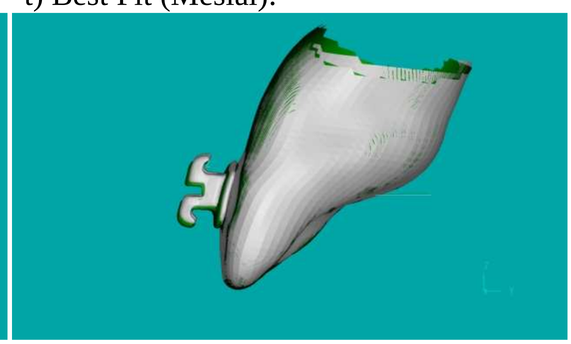


r) Move Both To Origin:

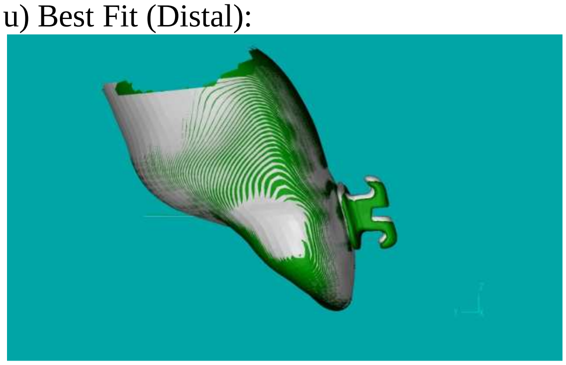


s) Best Fit (Facial):

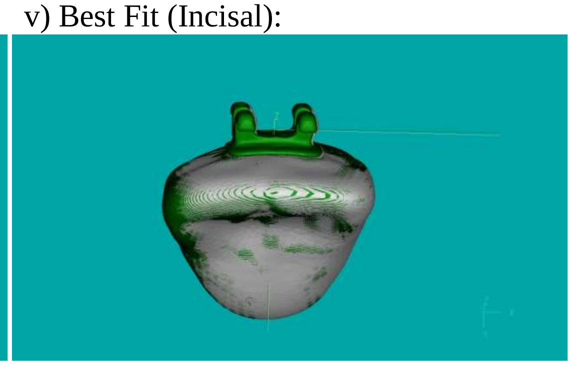
t) Best Fit (Mesial):



u) Best Fit (Distal):



v) Best Fit (Incisal):



w) Best Fit (Gingival):

Figure 4: Bracket Comparison Software Screen-Shots:

The bracket compare software provided an exportable table containing measurements taken from the superimposed models.

The bracket compare software allowed linear measurements of the differences between the two virtual models. There were six measurements taken for each bracket. Measurements were translational, one for each axis of interest, as well as angular. The linear translational measurements were reported in millimeter base units because most readers can readily contextualize this unit length. Linear measurement differences less than or equal to 0.5 mm were deemed "insignificant" and those greater than 0.5 mm were considered "significant". This value was chosen partially because the American Board of Orthodontics certification exam uses the value of 0.5 mm as the increment of difference which designates the deduction of points. The angulation measurements were reported in degree (0-360°) measurements. Angulation difference measurements less than or equal to 2° were deemed "insignificant" and those greater than 2° were deemed "significant".

The bracket compare software provided an output of the measured differences between bracket positioning on model set-up to the bracket positioning achieved clinically. These differences included both the magnitude of discrepancy as well as the direction in which it occurred, which was designated by either a positive or negative sign. Values for each measurement were either positive or negative, relating to which direction the bracket positioning error occurred. Table 2 displays the designations for positive and negative values for each dimension measured.

Table 2: Directionality of Bonding Error Key:

	Positive (+)	**Negative (-)**
M-D	Mesial	Distal
B-L	Lingual	Buccal
Vertical	Gingival	Occlusal
Torque	Lingual crown torque	Buccal crown torque
Tip	Distal root tip	Mesial root tip
Rotation	Mesial-lingual	Mesial-buccal

One-tailed t-tests for significance were completed to determine if the absolute values of the differences were within our acceptable range of 0.5 mm linearly and 2° angularly. One-tailed t-tests with a 95% confidence interval ($\alpha = 0.05$ mm) were applied to each of the 6 dimensions measured to test the hypothesis.

Frequency statistics were also computed to help describe the frequency of error, directionality, and tooth type biases from the indirect bonding method. Frequency data is being used in this study in two principal ways.

First, this study is concerned with uncovering bracket positioning biases. We have divided the data into errors that occur in the positive values and those that have negative values. The positive and negative values describe which direction the error occurred in each of the studied dimensions, i.e. buccal vs. lingual, mesial vs. distal, etc. These frequency biases are calculated for both the complete data set including all samples grouped together as well as data sets grouped together by specific tooth type. Biases stronger than 60% in one direction versus another were arbitrarily deemed clinically significant by the author and are highlighted below.

Secondly, frequency data is being used to determine how often a bracket was positioned within our predetermined acceptable range, +/- 0.5 mm along linear axes and 2 degrees along rotational axes. This data helps answer the essential question of how reliable is the indirect bonding process at achieving the intended bracket position. Again, the frequencies are calculated for both the complete data set including all samples grouped together as well as data sets grouped together by specific tooth type.

Finally, having the same operator, ML, re-measure 25 randomly selected bracket pairs, tested intra-rater reliability. Altman-Bland analysis supported that the new differences measured were within acceptable agreement with the original measurements.

Results:

Bracket Failures:

16 of the 163 brackets that were initially bonded failed or detached during the course of the study. Therefore, the complete bracket failure rate of the study is 0.098. Each of the discarded samples from the study is listed in Table 3.

Table 3: Discarded Observations

Bracket Failure	16
Bracket Repositioned	4
Software Error	8

Descriptive Error Statistics:

Composite error statistics were calculated for all of the brackets grouped together and are displayed in Table 4. Error statistics by subject are displayed in Table 5. Error statistics by quadrant are displayed in Table 6. Error statistics for anterior teeth grouped together (incisors and canines) and posterior teeth grouped together (premolars and molars) are displayed in Table 7. Error statistics by tooth type (incisors, canines, premolars, molars) are displayed in Table 8.

Table 4: Composite Error Statistics

	# Of Brackets	Mean	Median	Std Dev	Minimum	Maximum	Range
M-D (mm)	135	-0.007	-0.007	0.117	-0.531	0.316	0.847
B-L (mm)	135	0.001	-0.005	0.131	-0.484	0.731	1.215
Vertical (mm)	135	-0.025	-0.008	0.160	-0.516	0.349	0.865
Torque (°)	135	-0.120	-0.230	1.757	-5.250	7.320	12.570
Tip (°)	135	-0.159	-0.100	1.574	-5.080	3.940	9.020
Rotation (°)	135	-0.197	-0.100	1.374	-5.970	3.840	9.810

Table 5: Error Statistics by Subject:

Subject	# Of Brackets	Variable	Mean	Median	Std Dev	Minimum	Maximum	Range
1	22	M-D (mm)	-0.044	-0.013	0.143	-0.531	0.188	0.719
		B-L (mm)	-0.002	-0.010	0.073	-0.154	0.143	0.297
		Vertical (mm)	0.069	0.063	0.148	-0.448	0.293	0.741
		Torque (°)	-0.483	-0.600	1.084	-3.460	1.830	5.290
		Tip (°)	-0.139	-0.195	1.716	-5.080	3.770	8.850
		Rotation (°)	-0.068	-0.075	1.121	-2.670	2.760	5.430
2	15	M-D (mm)	-0.007	-0.011	0.101	-0.285	0.108	0.393
		B-L (mm)	-0.027	0.000	0.144	-0.484	0.201	0.685
		Vertical (mm)	0.015	-0.004	0.094	-0.132	0.205	0.337
		Torque (°)	-0.165	-0.110	1.131	-2.910	1.990	4.900
		Tip (°)	-0.083	0.120	0.687	-1.310	1.030	2.340
		Rotation (°)	-0.052	0.020	0.758	-0.970	1.150	2.120
3	13	M-D (mm)	0.043	0.067	0.097	-0.151	0.163	0.314
		B-L (mm)	-0.005	-0.020	0.085	-0.118	0.156	0.274
		Vertical (mm)	0.095	0.119	0.166	-0.192	0.349	0.541
		Torque (°)	-0.990	-1.820	2.137	-4.500	2.500	7.000
		Tip (°)	0.403	0.610	2.351	-4.680	3.940	8.620
		Rotation (°)	-0.605	-0.190	1.876	-4.290	2.100	6.390
4	7	M-D (mm)	-0.007	-0.047	0.141	-0.188	0.218	0.406
		B-L (mm)	-0.024	-0.008	0.082	-0.158	0.055	0.213
		Vertical (mm)	-0.011	-0.014	0.071	-0.121	0.107	0.228
		Torque (°)	-0.176	-0.390	1.499	-1.980	1.580	3.560
		Tip (°)	-0.163	0.640	2.264	-4.830	2.180	7.010
		Rotation (°)	-0.800	-0.980	1.820	-3.400	2.060	5.460
5	26	M-D (mm)	0.009	0.001	0.107	-0.194	0.211	0.405
		B-L (mm)	-0.008	-0.004	0.061	-0.140	0.129	0.269
		Vertical (mm)	0.007	0.008	0.114	-0.178	0.236	0.414
		Torque (°)	-0.545	-0.590	1.683	-3.390	4.060	7.450
		Tip (°)	0.019	0.045	1.733	-4.500	3.710	8.210
		Rotation (°)	-0.048	-0.035	0.893	-2.680	2.440	5.120
6	18	M-D (mm)	0.014	0.028	0.101	-0.196	0.174	0.370
		B-L (mm)	0.032	0.065	0.120	-0.171	0.231	0.402
		Vertical (mm)	-0.103	-0.111	0.105	-0.278	0.053	0.331
		Torque (°)	-0.248	-0.120	0.977	-2.680	1.370	4.050
		Tip (°)	-0.351	-0.410	0.986	-2.150	1.420	3.570
		Rotation (°)	-0.492	-0.450	0.719	-1.470	1.430	2.900
7	17	M-D (mm)	0.001	0.016	0.138	-0.314	0.316	0.630
		B-L (mm)	0.048	0.001	0.259	-0.319	0.731	1.050
		Vertical (mm)	-0.192	-0.134	0.195	-0.516	0.146	0.662
		Torque (°)	0.884	1.320	2.453	-5.250	3.720	8.970
		Tip (°)	-0.778	-0.420	1.681	-4.830	1.930	6.760
		Rotation (°)	-0.072	0.520	2.201	-5.970	3.290	9.260
8	17	M-D (mm)	-0.050	-0.040	0.098	-0.285	0.111	0.396
		B-L (mm)	-0.025	-0.056	0.132	-0.308	0.183	0.491
		Vertical (mm)	-0.079	-0.080	0.136	-0.384	0.101	0.485
		Torque (°)	0.858	0.760	2.064	-2.060	7.320	9.380
		Tip (°)	-0.127	-0.410	1.047	-1.410	2.130	3.540
		Rotation (°)	0.025	0.180	1.615	-4.200	3.840	8.040

Table 6: Error Statistics by Quadrant:

Quadrant	# Of Brackets	Variable	Mean	Median	Std Dev	Minimum	Maximum	Range
Lower Left	35	M-D (mm)	0.040	0.033	0.101	-0.214	0.211	0.425
		B-L (mm)	0.076	0.057	0.092	-0.115	0.314	0.429
		Vertical (mm)	-0.042	-0.013	0.173	-0.504	0.349	0.853
		Torque (°)	-0.304	-0.110	1.619	-4.500	2.800	7.300
		Tip (°)	-0.434	-0.500	1.665	-5.080	3.940	9.020
		Rotation (°)	-0.571	-0.390	1.468	-4.290	2.760	7.050
Lower Right	37	M-D (mm)	-0.062	-0.055	0.140	-0.531	0.218	0.749
		B-L (mm)	-0.046	-0.035	0.074	-0.210	0.143	0.353
		Vertical (mm)	-0.052	-0.027	0.159	-0.448	0.231	0.679
		Torque (°)	-0.020	0.050	1.715	-3.110	4.060	7.170
		Tip (°)	0.062	0.170	1.560	-4.830	3.770	8.600
		Rotation (°)	-0.327	-0.160	1.467	-5.970	2.440	8.410
Upper Left	29	M-D (mm)	0.006	0.013	0.109	-0.245	0.316	0.561
		B-L (mm)	0.070	0.031	0.150	-0.083	0.731	0.814
		Vertical (mm)	0.003	0.017	0.170	-0.516	0.257	0.773
		Torque (°)	-0.515	-0.630	2.210	-5.250	7.320	12.570
		Tip (°)	-0.311	-0.010	1.789	-4.830	3.710	8.540
		Rotation (°)	-0.195	-0.110	1.388	-4.200	3.840	8.040
Upper Right	34	M-D (mm)	-0.006	-0.008	0.088	-0.285	0.124	0.409
		B-L (mm)	-0.085	-0.076	0.126	-0.484	0.156	0.640
		Vertical (mm)	-0.001	0.008	0.137	-0.278	0.262	0.540
		Torque (°)	0.297	-0.140	1.453	-1.950	3.720	5.670
		Tip (°)	0.015	-0.065	1.285	-3.190	3.350	6.540
		Rotation (°)	0.325	0.025	1.010	-1.590	3.290	4.880

Table 7: Error Statistics by Anterior/Posterior Site:

Site	# Of Brackets	Variable	Mean	Median	Std Dev	Minimum	Maximum	Range
Anterior (Incisors & Canines)	80	M-D (mm)	-0.004	-0.005	0.102	-0.314	0.218	0.532
		B-L (mm)	0.006	-0.004	0.095	-0.210	0.241	0.451
		Vertical (mm)	-0.017	-0.003	0.149	-0.504	0.349	0.853
		Torque (°)	-0.062	-0.080	1.447	-4.500	4.060	8.560
		Tip (°)	-0.187	-0.025	1.493	-5.080	3.940	9.020
		Rotation (°)	-0.241	-0.075	1.458	-5.970	3.840	9.810
Posterior (Premolars & Molars)	55	M-D (mm)	-0.011	-0.007	0.137	-0.531	0.316	0.847
		B-L (mm)	-0.007	-0.011	0.171	-0.484	0.731	1.215
		Vertical (mm)	-0.036	-0.027	0.175	-0.516	0.293	0.809
		Torque (°)	-0.205	-0.410	2.140	-5.250	7.320	12.570
		Tip (°)	-0.118	-0.190	1.699	-4.830	3.770	8.600
		Rotation (°)	-0.135	-0.110	1.254	-4.200	3.290	7.490

Table 8: Error Statistics by Tooth Type:

Type	# Of Brackets	Variable	Mean	Median	Std Dev	Minimum	Maximum	Range
Canine	26	B-L (mm)	-0.053	0.086	-0.031	-0.241	0.156	0.397
		M-D (mm)	0.013	0.078	0.009	-0.111	0.218	0.329
		Vertical (mm)	0.034	0.128	0.005	-0.224	0.294	0.518
		Rotate (°)	0.210	1.286	0.000	-2.680	4.290	6.970
		Tip (°)	-0.198	1.420	-0.055	-4.680	3.350	8.030
		Torque (°)	-0.228	1.126	-0.050	-2.470	2.600	5.070
Incisor (Central & Laterals)	54	B-L (mm)	-0.054	0.076	-0.041	-0.222	0.120	0.342
		M-D (mm)	-0.012	0.111	-0.009	-0.314	0.188	0.502
		Vertical (mm)	0.026	0.157	0.013	-0.349	0.504	0.853
		Rotate (°)	0.235	1.548	0.010	-5.970	4.150	10.120
		Tip (°)	0.061	1.549	-0.005	-5.080	4.830	9.910
		Torque (°)	0.103	1.579	0.085	-4.060	4.500	8.560
Molar (1^{st} and 2^{nd})	10	B-L (mm)	-0.045	0.096	-0.074	-0.154	0.143	0.297
		M-D (mm)	-0.063	0.206	-0.033	-0.531	0.211	0.742
		Vertical (mm)	0.035	0.168	0.017	-0.167	0.448	0.615
		Rotate (°)	0.405	1.114	0.335	-1.120	2.680	3.800
		Tip (°)	-0.213	2.735	-0.445	-3.770	4.500	8.270
		Torque (°)	-0.268	2.016	-0.520	-3.390	3.110	6.500
Premolar (1^{st} and 2^{nd})	46	B-L (mm)	-0.492	0.652	-0.062	-1.057	0.083	1.887
		M-D (mm)	-0.380	0.584	0.003	-1.510	0.316	1.826
		Vertical (mm)	0.216	0.360	0.053	-0.516	9.161	9.677
		Rotate (°)	-0.040	1.421	0.010	-4.230	4.200	8.430
		Tip (°)	-0.047	1.429	-0.145	-2.870	4.830	7.700
		Torque (°)	0.401	2.506	-0.415	-5.250	8.810	14.060

The data was also plotted to describe the pattern of discrepancy in bracket positioning in each of the 6 dimensions. For each dimension, the data is presented in quadrants to which assists in visualizing regional location effects on the accuracy of the indirect bonding procedure. The plots are available in Appendix I (a-f).

T-Tests for Significance (Hypothesis Testing):

The results of the one-tailed t-tests for significance are presented in Figure 5 (a-f). All six one-sided t-tests reached significance (at α = 0.05, i.e., confidence = 95%), so we reject the hypothesis (H0) of means greater than or equal to the 0.5 mm and 2° specifications. Along the horizontal (x) axis for linear variables, values are reported as absolute values in millimeters. Along the horizontal (x) axis for angular variables, the values are reported as absolute values in degrees.

One-sided t-tests for linear variables

H0: μ < 0.5 mm
HA: μ ≥ 0.5 mm

Variable: Mesial-Distal (Absolute Values)

N	*Mean*	*Std Dev*	*Std Err*	*Minimum*	*Maximum*
135	0.0872	0.0781	0.00672	0.00100	0.5310

DF	*t Value*	*Pr < t*
134	-61.41	<.0001

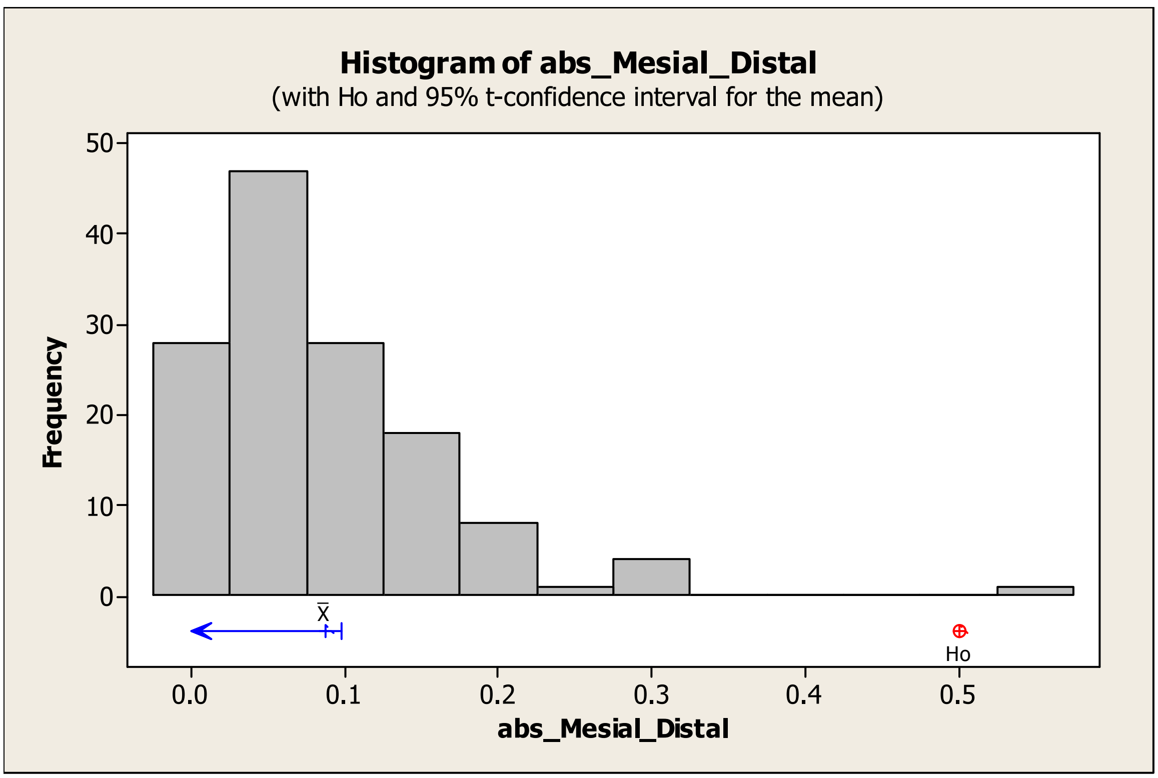


Figure 5a: t-tests for Significance for Mesial-Distal Mean Error

One-sided t-tests for linear variables

H0: $\mu < 0.5$ mm
HA: $\mu \geq 0.5$ mm

Variable: Buccal-Lingual (Absolute Values)

N	*Mean*	*Std Dev*	*Std Err*	*Minimum*	*Maximum*
135	0.0901	0.0950	0.00817	0	0.7310

DF	*t Value*	*Pr < t*
134	-50.14	<.0001

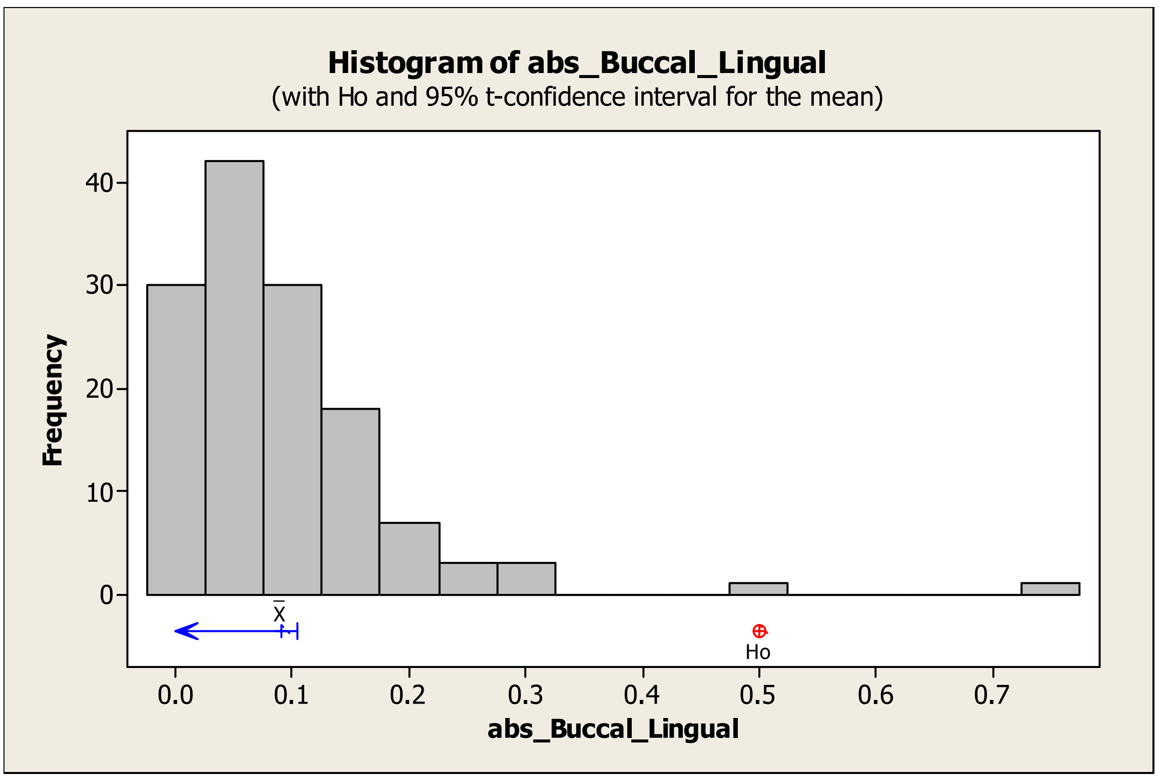


Figure 5b: t-tests for Significance Buccal-Lingual Mean Error

One-sided t-tests for linear variables

H0: μ < 0.5 mm
HA: μ ≥ 0.5 mm

Variable: Vertical (Absolute Values)

N	*Mean*	*Std Dev*	*Std Err*	*Minimum*	*Maximum*
135	0.1181	0.1103	0.00949	0.00200	0.5160

DF	*t Value*	*Pr < t*
134	-40.24	<.0001

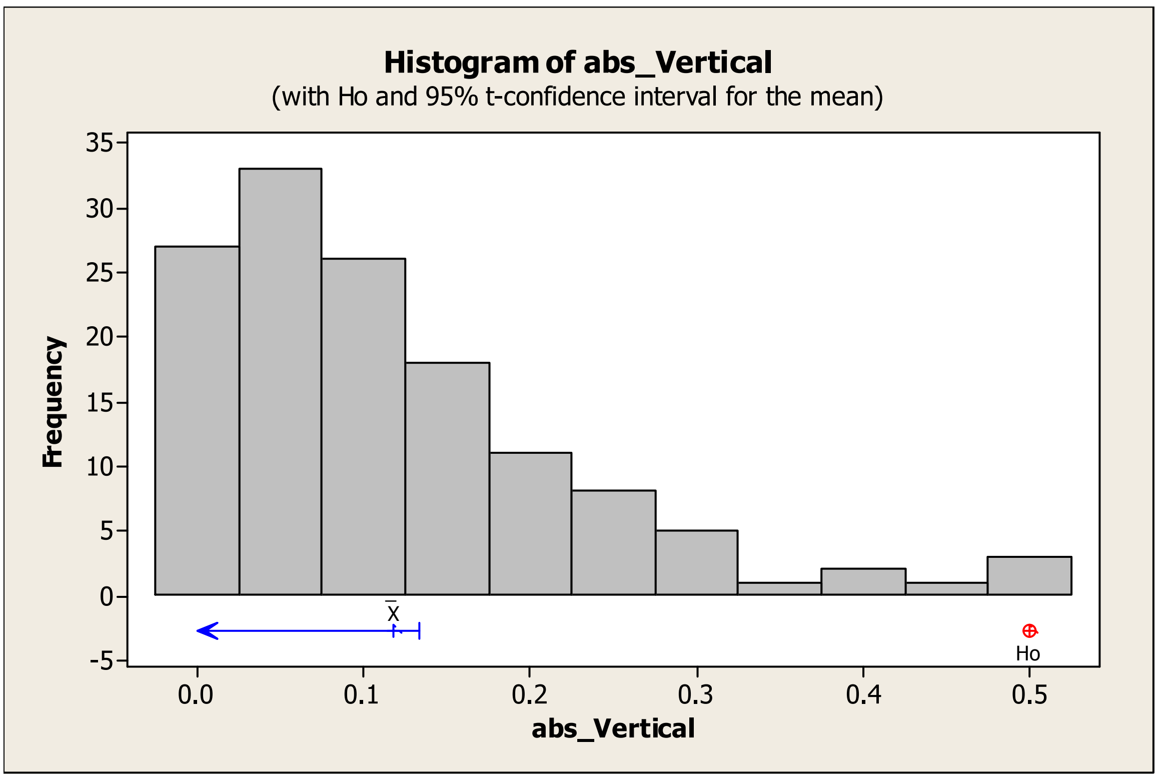


Figure 5c: t-tests for Significance Vertical Mean Error

One-sided t-tests for angular variables

H0: $\mu < 2°$
HA: $\mu \geq 2°$

Variable: Torque (Absolute Values)

N	*Mean*	*Std Dev*	*Std Err*	*Minimum*	*Maximum*
135	1.3106	1.1705	0.1007	0	7.3200

DF	*t Value*	*Pr < t*
134	-6.84	<.0001

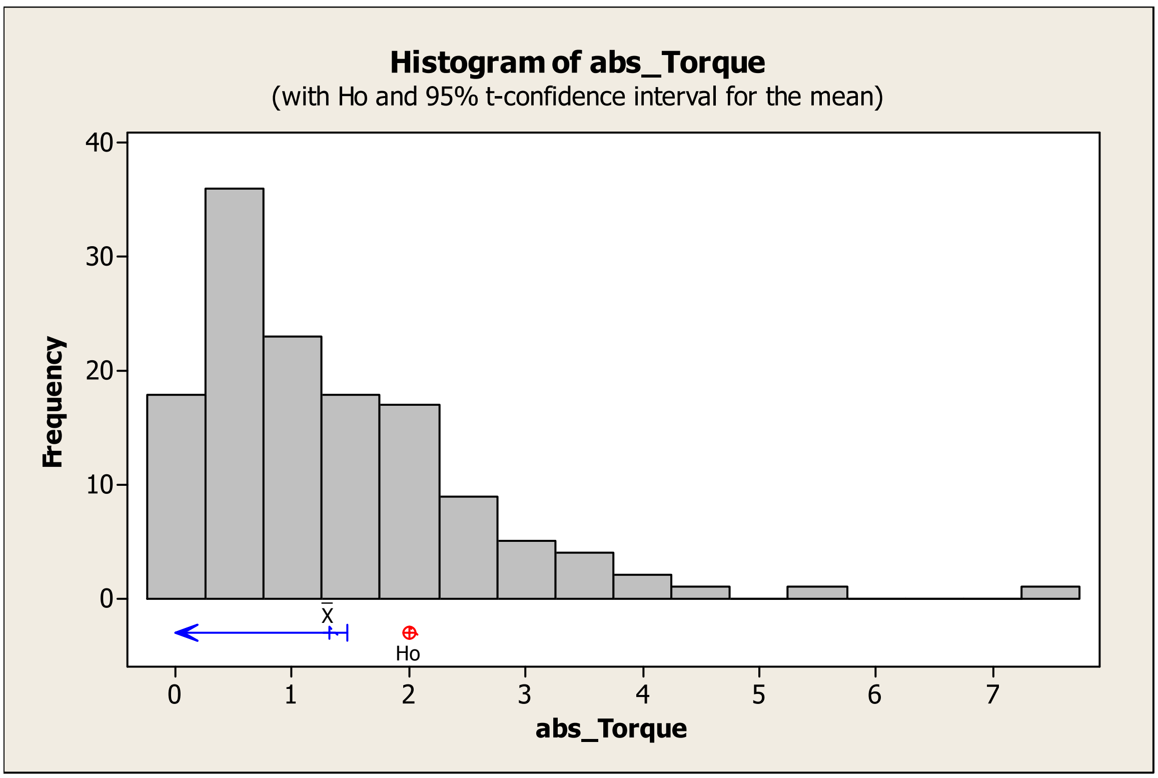


Figure 5d: t-tests for Significance Torque Mean Error

One-sided t-tests for angular variables

H0: μ < 2°
HA: μ ≥ 2°

Variable: Tip (Absolute Values)

N	*Mean*	*Std Dev*	*Std Err*	*Minimum*	*Maximum*
135	1.1113	1.1223	0.0966	0.0100	5.0800

DF	*t Value*	*Pr < t*
134	-9.20	<.0001

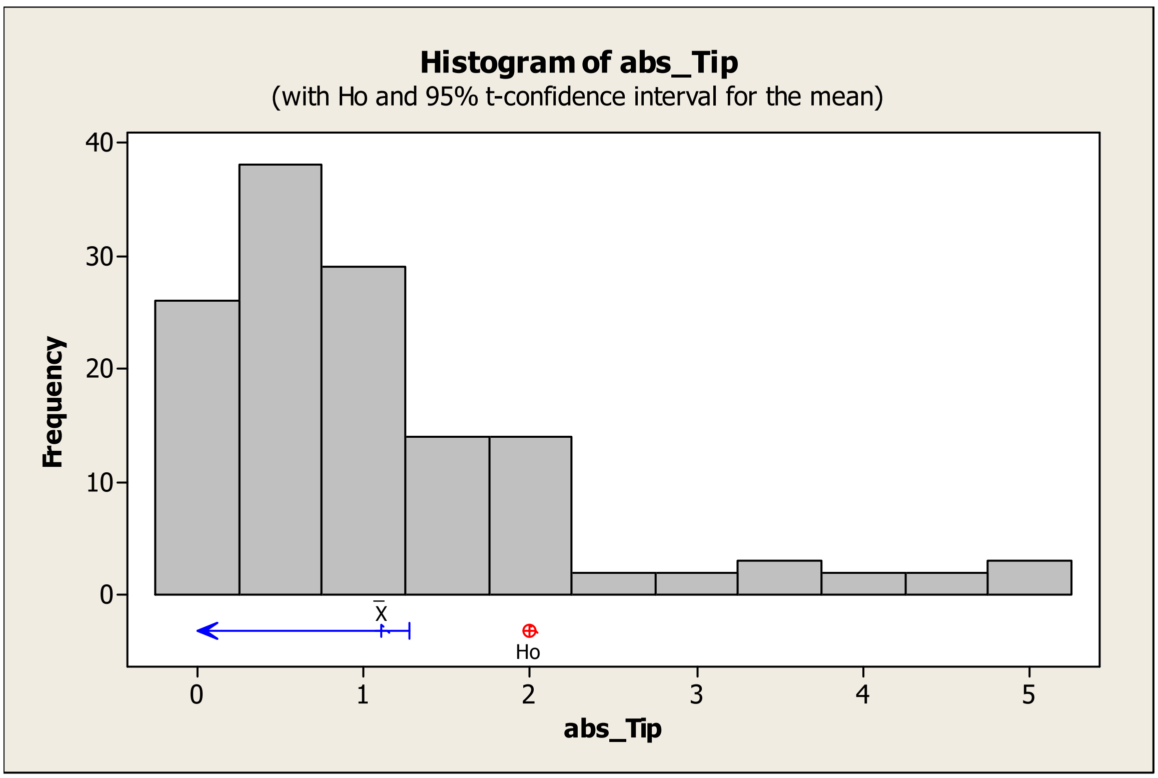


Figure 5e: t-tests for Significance Tip Mean Error

One-sided t-tests for angular variables

H0: $\mu < 2°$
HA: $\mu \geq 2°$

Variable: Rotation (Absolute Values)

N	*Mean*	*Std Dev*	*Std Err*	*Minimum*	*Maximum*
135	0.9465	1.0128	0.0872	0	5.9700

DF	*t Value*	*Pr < t*
134	-12.09	<.0001

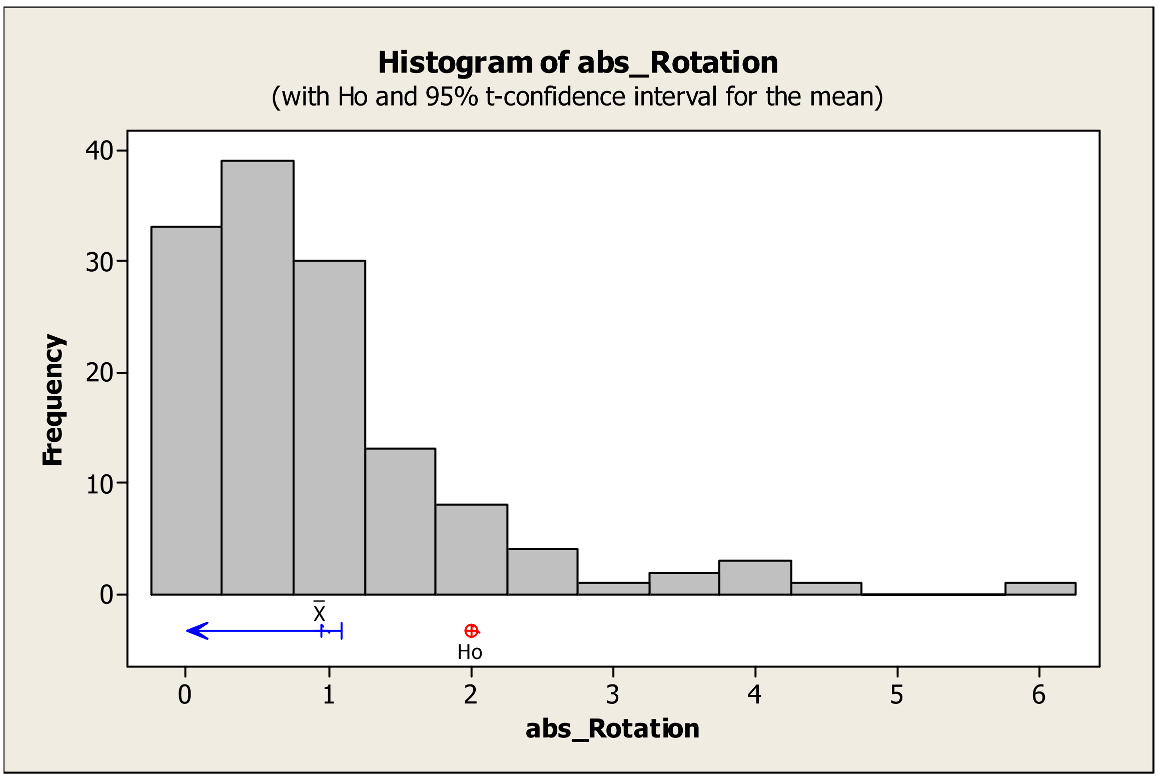


Figure 5f: t-tests for Significance Rotation Mean Error

Frequency of Error Statistics:

Frequency data is reported in Table 9 (a-f) and Table 10 (a-f). This data is also displayed in graphical form in Appendices II (a-f) and III (a-f). Table 9 (a-f) lists directional biases.

Table 9a: Mesial-Distal Frequency of Directional Bias

Frequency of Error in Mesial-Distal Dimension:			
	Distal	Mesial	Total
Incisor	30	24	54
Canine	12	14	26
Premolar	23	23	46
Molar	7	3	10
Total	72	64	136

Percentage of Error in Mesial-Distal Dimension:		
	Distal	Mesial
Incisor	55.56	44.44
Canine	46.15	53.85
Premolar	50.00	50.00
Molar*	70.00	30.00
Total	52.94%	47.06%

Table 9b: Buccal-Lingual Frequency of Directional Bias

Frequency of Error in Buccal-Lingual Dimension:			
	Buccal	Lingual	Total
Incisor	44	10	54
Canine	20	6	26
Premolar	37	9	46
Molar	7	3	10
Total	108	28	136

Percentage of Error in Buccal-Lingual Dimension:		
	Buccal	Lingual
Incisor*	81.48	18.52
Canine*	76.92	23.08
Premolar*	80.43	19.57
Molar*	70.00	30.00
Total*	79.41%	20.59%

Table 9c: Vertical Frequency of Directional Bias

Frequency of Error in Vertical Dimension:			
	Occlusal	Gingival	Total
Incisor	23	31	54
Canine	10	16	26
Premolar	17	29	46
Molar	4	6	10
Total	54	82	136

Percentage of Error in Vertical Dimension:		
	Occlusal	Gingival
Incisor	42.59	57.41
Canine*	38.46	61.54
Premolar*	39.96	63.04
Molar*	40.00	60.00
Total*	39.71%	60.29%

Table 9d: Torque Frequency of Directional Bias

Frequency of Error in Torque:			
	Bu. Crn. Torque	Li. Crn. Torque	Total
Incisor	26	28	54
Canine	15	11	26
Premolar	27	19	46
Molar	6	4	10
Total	74	62	136

Percentage of Error in Torque:		
	Bu. Crn. Torque	Li. Crn. Torque
Incisor	48.15	51.85
Canine	57.69	42.31
Premolar	58.70	41.30
Molar*	60.00	40.00
Total	54.41%	45.59%

Table 9e: Tip Frequency of Directional Bias

Frequency of Error in Tip:			
	MRT	DRT	Total
Incisor	27	27	54
Canine	15	11	26
Premolar	26	20	46
Molar	7	3	10
Total	75	61	136

Percentage of Error in Tip:		
	MRT	DRT
Incisor	50.00	50.00
Canine	57.69	42.31
Premolar	56.52	43.48
Molar*	70.00	30.00
Total	55.15%	44.85%

Table 9f: Rotation Frequency of Directional Bias

Frequency of Error in Rotation:			
	Mesial-Distal	Mesial-Lingual	Total
Incisor	27	27	54
Canine	13	13	26
Premolar	23	23	46
Molar	4	6	10
Total	67	69	136

Percentage of Error in Rotation:		
	Mesial-Distal	Mesial-Lingual
Incisor	50.00	50.00
Canine	50.00	50.00
Premolar	50.00	50.00
Molar*	40.00	60.00
Total	49.26%	50.74%

Table 10 (a-f) displays frequency and percentage of errors that occurred within and outside of our pre-determined acceptable ranges (+/- 0.5 mm linearly, 2° angularly).

Table 10a: Mesial-Distal Frequency of Positioning within Acceptable Range

Frequency within Range Mesial-Distal:			
	Outside	Within	Total
Incisor	0	54	54
Canine	0	26	26
Premolar	1	45	46
Molar	1	9	10
Total	2	134	136

Percentage within Range Mesial-Distal:		
	Outside	Within
Incisor	0.00	1.00
Canine	0.00	1.00
Premolar	0.02	0.98
Molar	0.10	0.90
Total	1.47%	98.53%

Table 10b: Buccal-Lingual Frequency of Positioning within Acceptable Range

Frequency within Range Buccal-Lingual:			
	Outside	Within	Total
Incisor	0	54	54
Canine	0	26	26
Premolar	2	44	46
Molar	0	10	10
Total	2	134	136

Percentage within Range Buccal-Lingual:		
	Outside	Within
Incisor	0.00	1.00
Canine	0.00	1.00
Premolar	0.04	0.96
Molar	0.00	1.00
Total	1.47%	98.53%

Table 10c: Vertical Frequency of Positioning within Acceptable Range

Frequency within Range Vertical:			
	Outside	Within	Total
Incisor	2	52	54
Canine	0	26	26
Premolar	2	44	46
Molar	0	10	10
Total	4	132	136

Percentage within Range Vertical:		
	Outside	Within
Incisor	0.04	0.96
Canine	0.00	1.00
Premolar	0.04	0.96
Molar	0.00	1.00
Total	2.94%	97.06%

Table 10d: Torque Frequency of Positioning within Acceptable Range

Frequency within Range Torque:			
	Outside	Within	Total
Incisor	8	46	54
Canine	2	24	26
Premolar	14	32	46
Molar	3	7	10
Total	27	109	136

Percentage within Range Torque:		
	Outside	Within
Incisor	0.15	0.85
Canine	0.08	0.92
Premolar	0.30	0.70
Molar	0.30	0.70
Total	19.85%	80.15%

Table 10e: Tip Frequency of Positioning within Acceptable Range

Frequency within Range Tip:			
	Outside	Within	Total
Incisor	6	48	54
Canine	2	24	26
Premolar	7	39	46
Molar	5	5	10
Total	20	116	136

Percentage within Range Tip:		
	Outside	Within
Incisor	0.11	0.89
Canine	0.08	0.92
Premolar	0.15	0.85
Molar	0.50	0.50
Total	14.71%	85.29%

Table 10f: Rotation Frequency of Positioning within Acceptable Range

Frequency within Range Rotation:			
	Outside	Within	Total
Incisor	7	47	54
Canine	3	23	26
Premolar	6	40	46
Molar	1	9	10
Total	17	119	136

Percentage within Range Rotation:		
	Outside	Within
Incisor	0.13	0.87
Canine	0.12	0.88
Premolar	0.13	0.87
Molar	0.10	0.90
Total	12.50%	87.50%

The percentage of brackets that were positioned within the acceptable range by tooth type is displayed graphically in Figure 6.

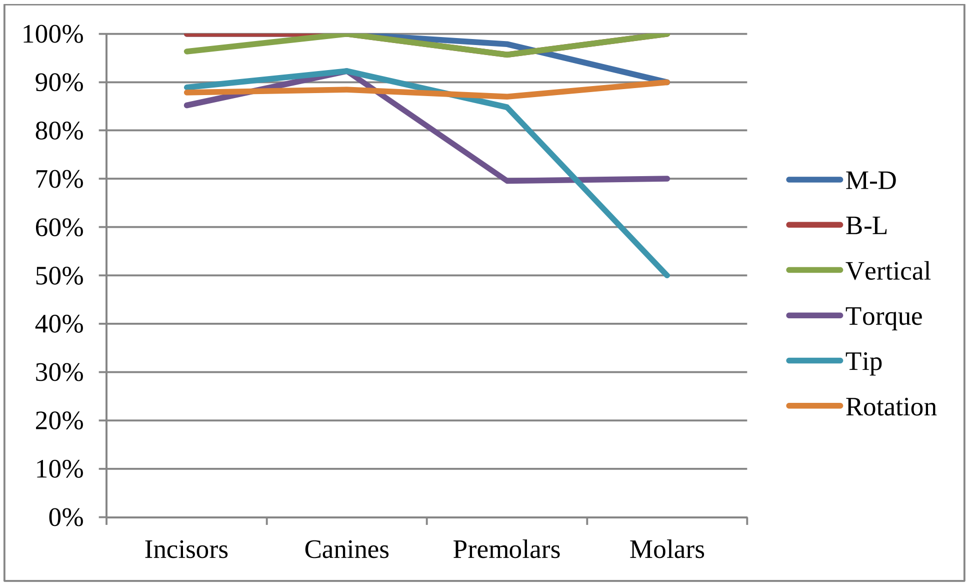


Figure 6: Percentage within Acceptable Range by Tooth Type:

Discussion:

Indirect bonding methods have been developed to aid the orthodontist in placing brackets accurately and reliably without many of the clinical challenges experienced with direct bonding. The work presented in this study aims at clarifying how well the transfer occurs between the indirect model set-up to the patient's actual teeth.

This study provides insights into positional accuracy and reliability in several ways. Specifically, how often bracket failures occur, the direction and frequency of indirect bonding errors, as well as how frequently the brackets "hit-the-target" and are placed within clinically acceptable boundaries were all tested. The study also investigated several clinical assumptions the author held about the pattern of indirect bonding errors.

One of the assumptions held prior to completion of the study was that posterior brackets would have higher incidence of failure and positioning error. In this study, posterior brackets (premolars and molars) did show a slightly higher frequency of being positioned outside the desired boundaries. However, it was not significantly different than anterior brackets (incisors and canines). This was most true for mesial-distal, torque, and tip. Additionally, posterior teeth also experienced the most failures in this study. Molars were the most directionally biased teeth. A potential explanation for this finding is that it is more difficult to hold indirect transfer trays as precisely and steadily in the molar region than in other areas of the mouth because of decreased access. This finding may also be partially explained by the low sample size of molar brackets included in the study.

Low sample sizes allow for small amounts of random error to significantly affect results and clinical interpretation.

Another assumption was that most vertical positioning errors should be biased towards the occlusal because incompletely seating the indirect transfer tray is seemingly more likely than an operator “over-seating” a tray during the clinical bonding procedure. The data suggest, however, that the opposite occurred, as most errors in the vertical direction occurred gingivally. All tooth types were positioned more gingival than intended 60% of the time. Gingival positioning errors could possibly imply that the indirect transfer trays may be “stretched” during the clinical bonding procedure by the operator’s fingers pressing the tray gingivally. The vinyl polysiloxane putty used in the tray exhibits elastic properties and thus absolute rigidity during seating cannot be assumed. Stretching of the transfer tray could also occur if the tray’s occlusal coverage was not adequate enough to prevent overseating or the tray stretched and “rolled” facially and gingivally under finger pressure. Because each operator applies a unique magnitude and vector of pressure when clinically seating the trays, this variable would need additional control in future studies.

Thirdly, it was expected that due to additional adhesive being applied to the brackets and teeth during the clinical bonding procedure, we would see a buccal-lingual bias towards the buccal. This bias was observed in the data with 79% of brackets being positioned more buccally than intended. In the other 21%, which were positioned more towards the lingual, it is possible that portions of the cured composite on the bracket base could have been thinned or lost during the lab procedure taking place after the first CBCT scan. The most likely time for this to have occurred is during tray removal from the stone model. If the entire bracket base was lost at some point before the clinical bonding procedure, these brackets may fail. This possible scenario could be one of the contributing factors to the complete bracket failure rate as well as to the number of lingually positioned brackets.

When comparing the results of the present work to other literature, it appears that the mean error in the mesial-distal (-0.007 mm), buccal-lingual (0.001 mm), and vertical (-0.025 mm) axes are less than reported by the 2008 in-vitro study by Wendl et al. (0.15 mm, 0.17 mm, and 0.19 mm). However, both studies report mean error values within the +/-0.5 mm acceptable range defined in this study.

When interpreting the data acquired in this study, it is also important to note that the errors refer to the positioning of the bracket, not the resulting effect on the tooth. For example, a value of -0.30 mm for a particular sample would reflect that the bracket was bonded 0.30 mm more to the distal than was originally intended based on the indirect model set-up.

The methods used in the study present a novel protocol to evaluate indirect bonding transfer errors in-vivo with digital 3-D imaging. The benefit of using digitally acquired 3-D surface data versus photographically acquired image data of bracket positioning errors is that they allow for precise and repeatable measurements in all 6 dimensions.

Importantly, the methods allowed for data to be acquired without additional radiation exposure to the patient and without any additional appointments.

Since each tooth/bracket pair was an independent unit, any changes in relative tooth position that occurred between the bonding appointment and when the in-vivo CBCT scan was completed were irrelevant. Assuming accurate impressioning and stone model pour-up techniques, absence of acute enamel attrition, interproximal stripping, or other dental pathology that could alter tooth shape, the tooth crown surfaces were identical from the first model to the second. Both models shared common tooth surfaces, therefore each tooth was superimposed using a best-fit method of those surfaces.

Although the methods used in the study provide a novel approach to studying indirect bonding errors, there are several additional controls and enhancements that would improve the study protocol. The multi-operator nature of the clinical bonding procedure could have been controlled more adequately with a single-operator protocol to reduce variability of the intra-oral technique. Conversely, however, it could be argued that by having different orthodontic graduate students placing the brackets, the results could be more generalizable than if a single, experienced orthodontist placed all of the trays themselves. It was not possible to control for operator of this aspect of the present study due to clinical constraints.

Another critique of the current protocol is the small sample size of molar brackets included in the study. It is difficult to achieve statistical or practical understanding of the positioning errors of molar brackets with sample size as low as ten brackets. Increasing sample sizes also allows for more specific analysis of each tooth type to further elucidate the local factors contributing to bracket positioning errors.

Future studies regarding the transfer accuracy of indirect bonding techniques should be completed to further our understanding of this process. Alternative indirect bonding methods should also be evaluated to compare with the results of the current study. Specifically, methods using rigid trays, bi-laminar trays, and/or customized single-tooth jigs should be studied. The indirect bonding transfer errors of made-to-order appliances such as Insignia® (Ormco) must also be examined. The clinical effectiveness of appliances that are founded upon the precise placement of customized brackets onto tooth surfaces could be significantly affected by transfer errors.

Forthcoming studies would benefit from more control over the clinical aspects of the bonding procedure to eliminate operator-induced biases in bracket positioning. Finally, with the development of new digital 3-D scanning technologies, more accurate data capture could be possible in future studies of this kind. Being able to capture more complete and accurate volumetric data will only improve our ability to measure differences in bracket positioning due to indirect bonding transfer error.

Technological advances such as digitally generated customized archwires may make indirect bonding more attractive to practicing orthodontists. Using a 3-D digital scan of the indirect bracket positioning on the stone models, a clinician could also fabricate a customized archwire from the same digital scan prior to the patient having brackets placed. Practically, the customized wire can be fabricated and placed the same date as the patient has the brackets bonded to their teeth. Also, this protocol would avoid the added radiation exposure of having another CBCT taken on the patient or forego intra-oral scanning needed to capture bracket positioning for fabrication of the customized archwire. This combined protocol could provide clinical and treatment efficiencies beyond those achieved through either indirect bonding or customized archwires alone.

The present study provides evidence that there is modest error in the indirect bonding transfer of brackets from the stone model to the patient's dentition. The data supports the null hypothesis that there is no *statistical* difference between the indirect set-up and the final bracket positioning. However, there were enough complete bracket failures (detachments) and positioning errors outside the acceptable range to raise questions about the reliability of this method *clinically*. The individual clinician will need to determine if these infrequent errors are acceptable as they consider indirect bonding within their practice.

Conclusions:

- The indirect bonding method investigated in this study *was accurate and reliable* within the specified acceptable boundaries of +/- 0.05 mm linearly and 2.0° angularly. For each of the 6 linear and angular dimensions, average bracket positioning was deemed to be statistically accurate at a 95% confidence interval, ($p<0.0001$). Bracket positioning errors were within acceptable boundaries 80.15 - 98.53% of the time.
- Directional and tooth type biases were also found in this present study. Brackets positioned with this indirect method were more buccal (79%) and gingival (60%) for all tooth types. Posterior teeth were more frequently malpositioned than anterior teeth, but due to small sample size, the significance cannot be statistically verified.
- The bracket failure (detachment) rate in this study was 9.8% between the time of initial bonding and subsequent final scan.

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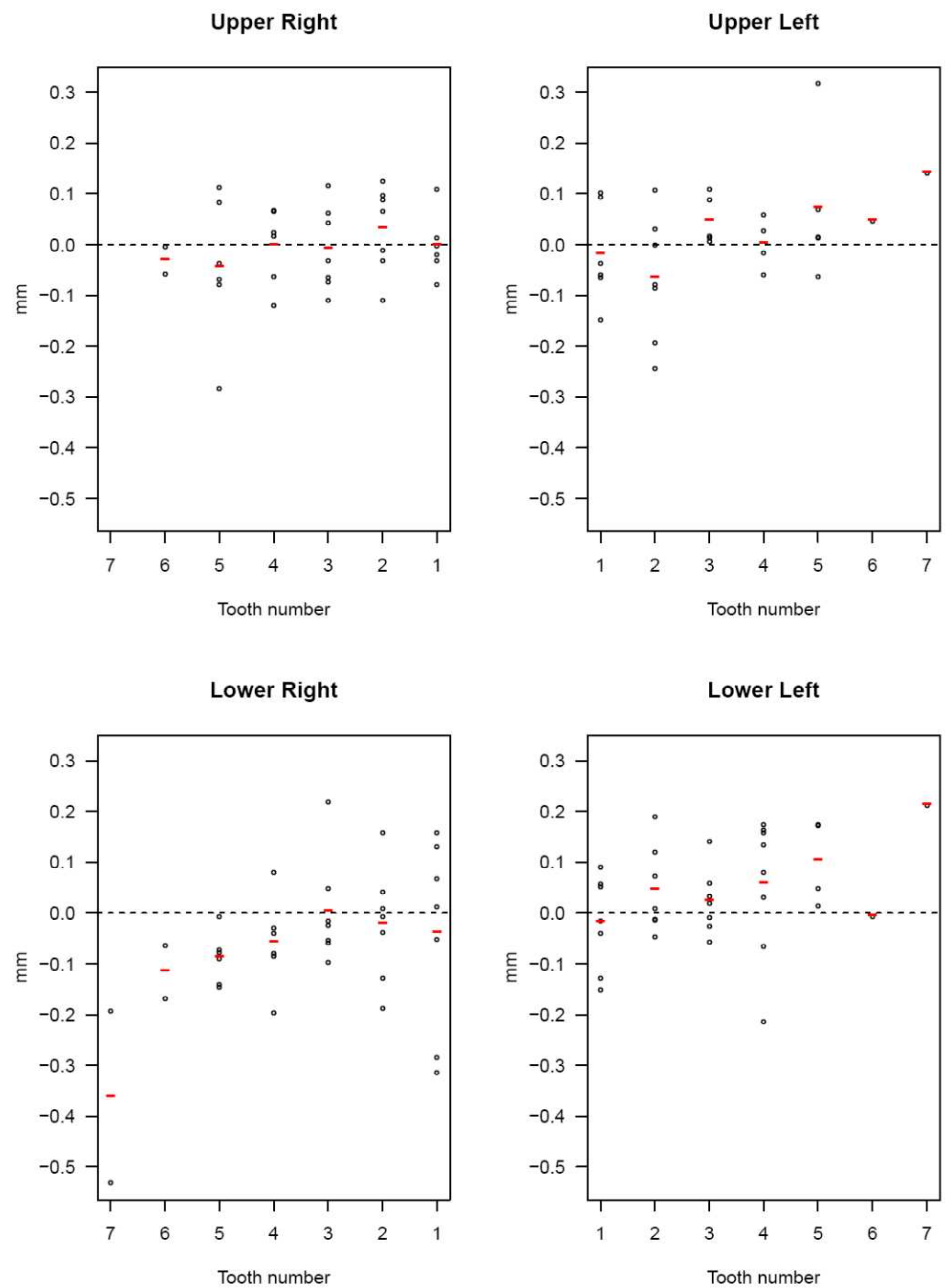
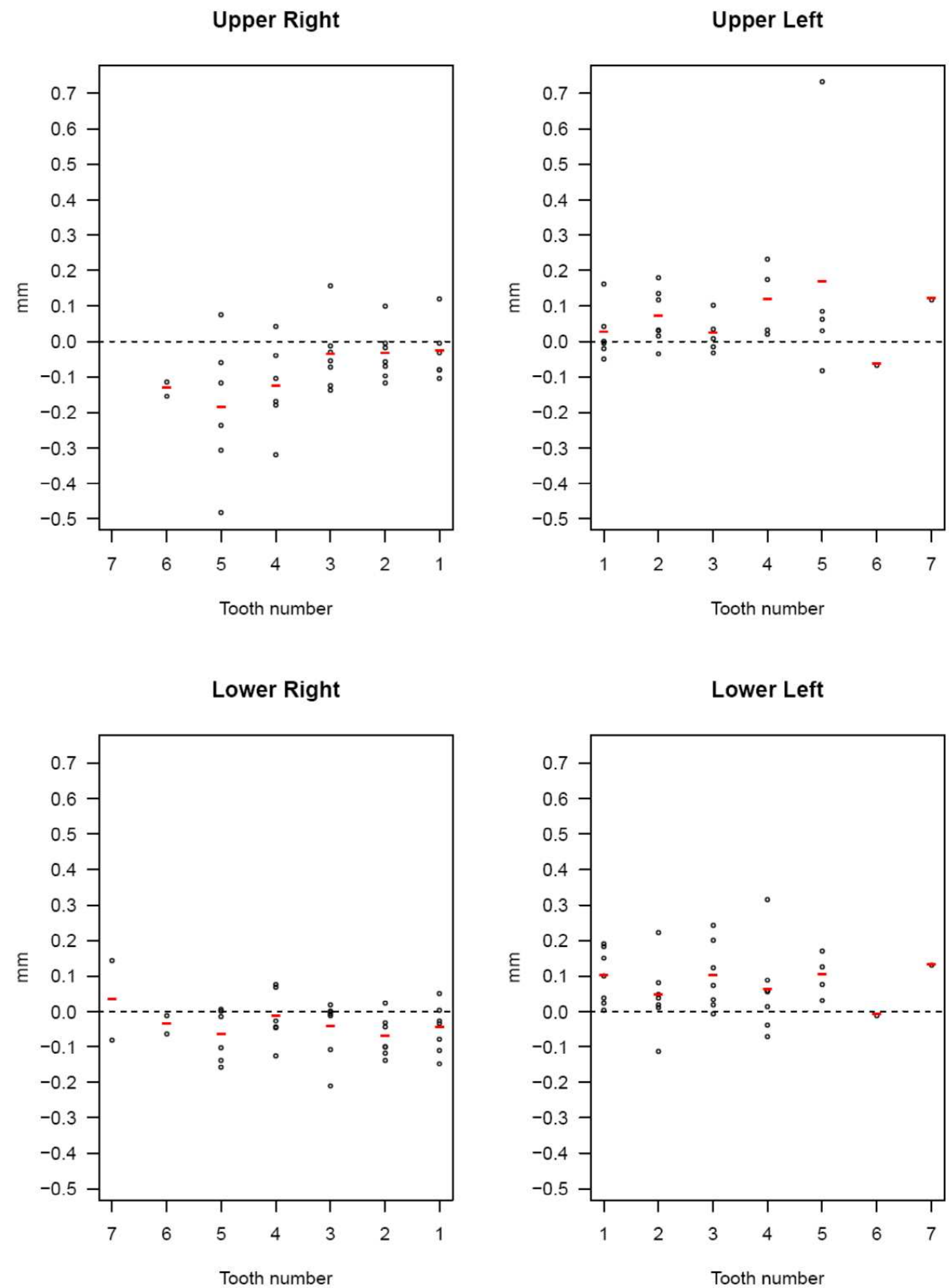
Appendix I: Data Plots of Error Data

The red dash designates the mean bracket position on each of the following data plots.



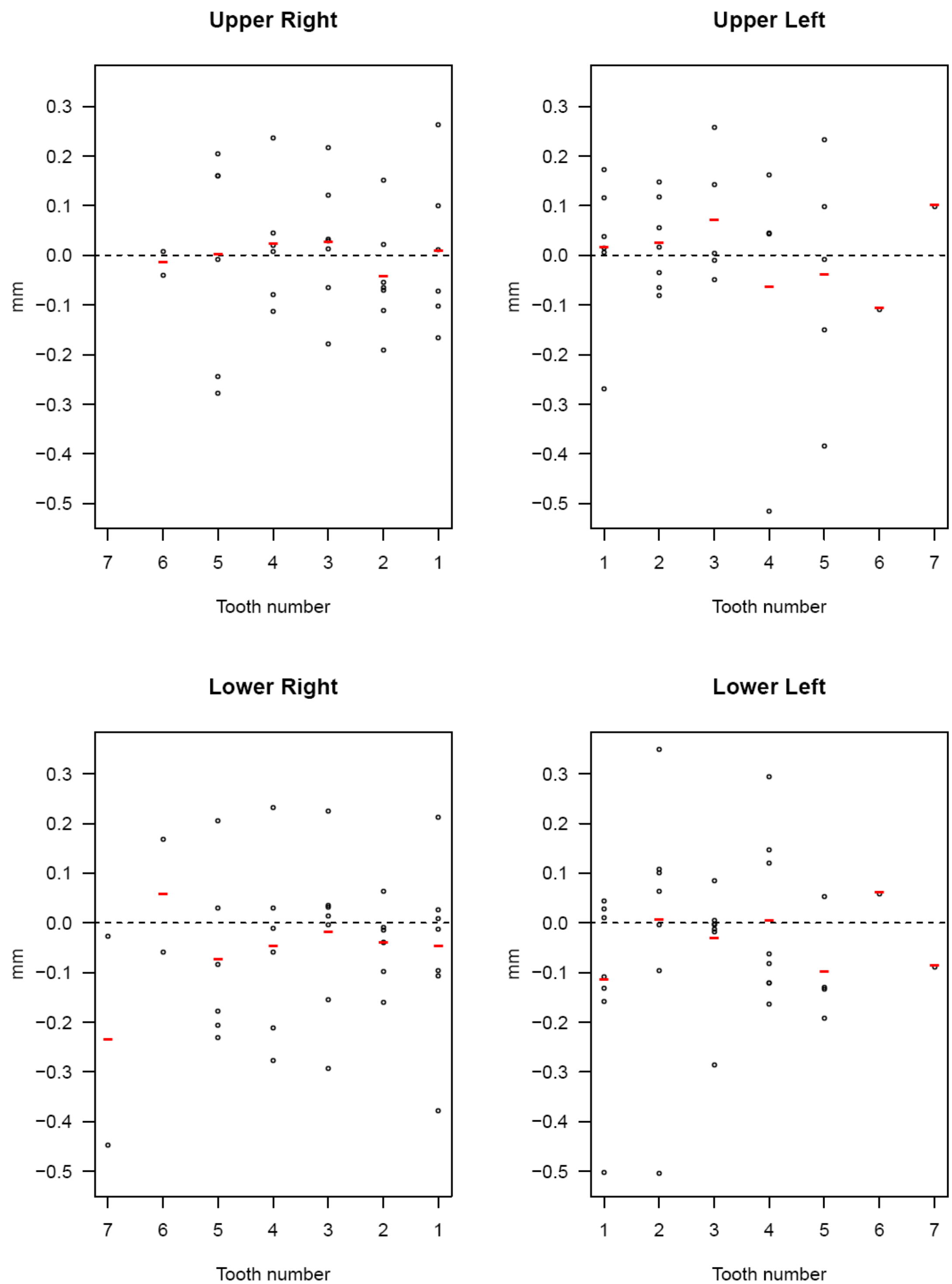
Subject 3 LR4 measurement was removed because it was an outlier. 3 measurements were also removed due to software error.Tooth means are denoted by a red −.

Appendix Ia: Mesial-Distal Data Plot



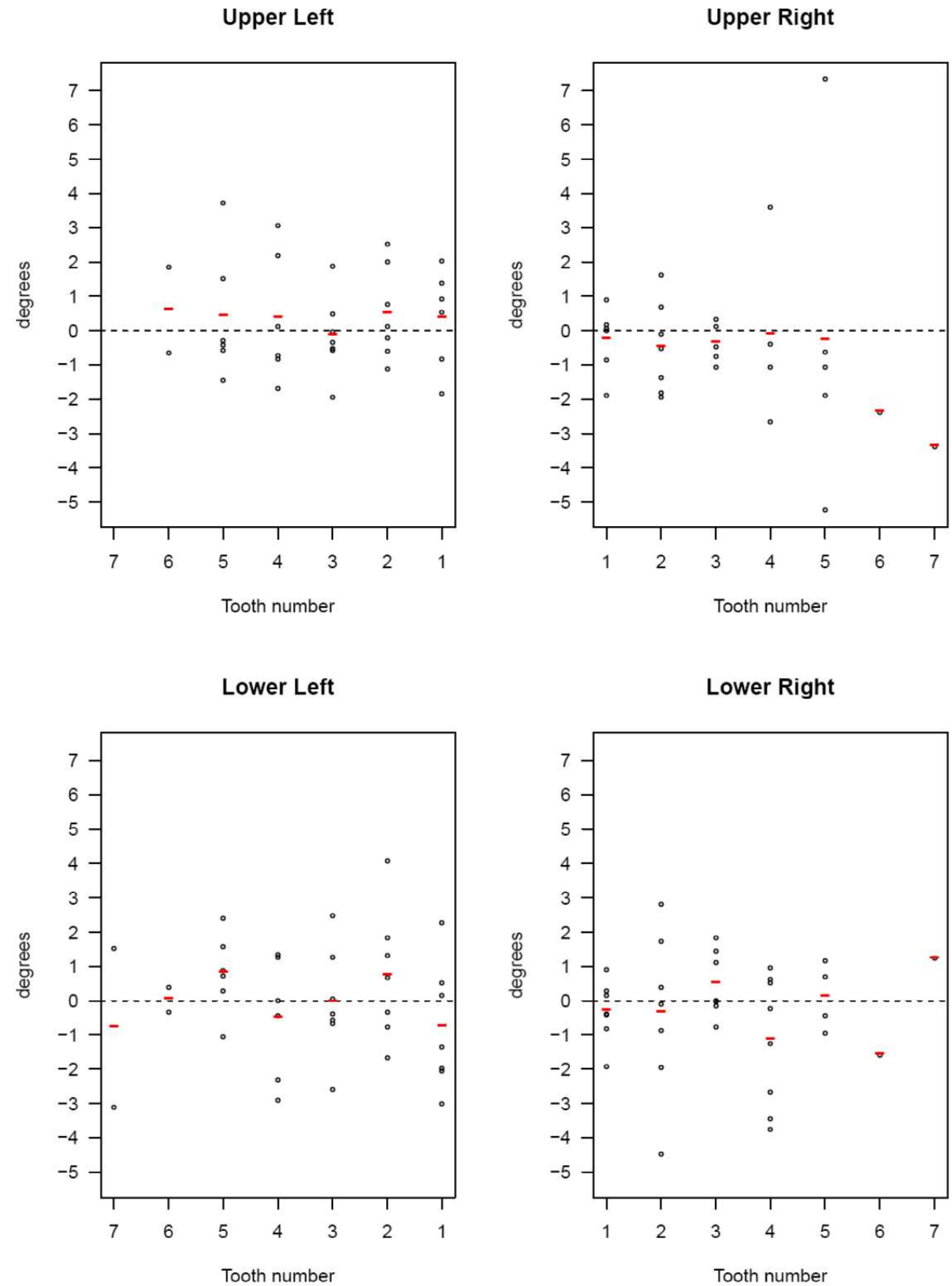
Subject 3 LR4 measurement was removed because it was an outlier. 3 measurements were also removed due to software error.Tooth means are denoted by a red −.

Appendix Ib: Buccal-Lingual Data Plot



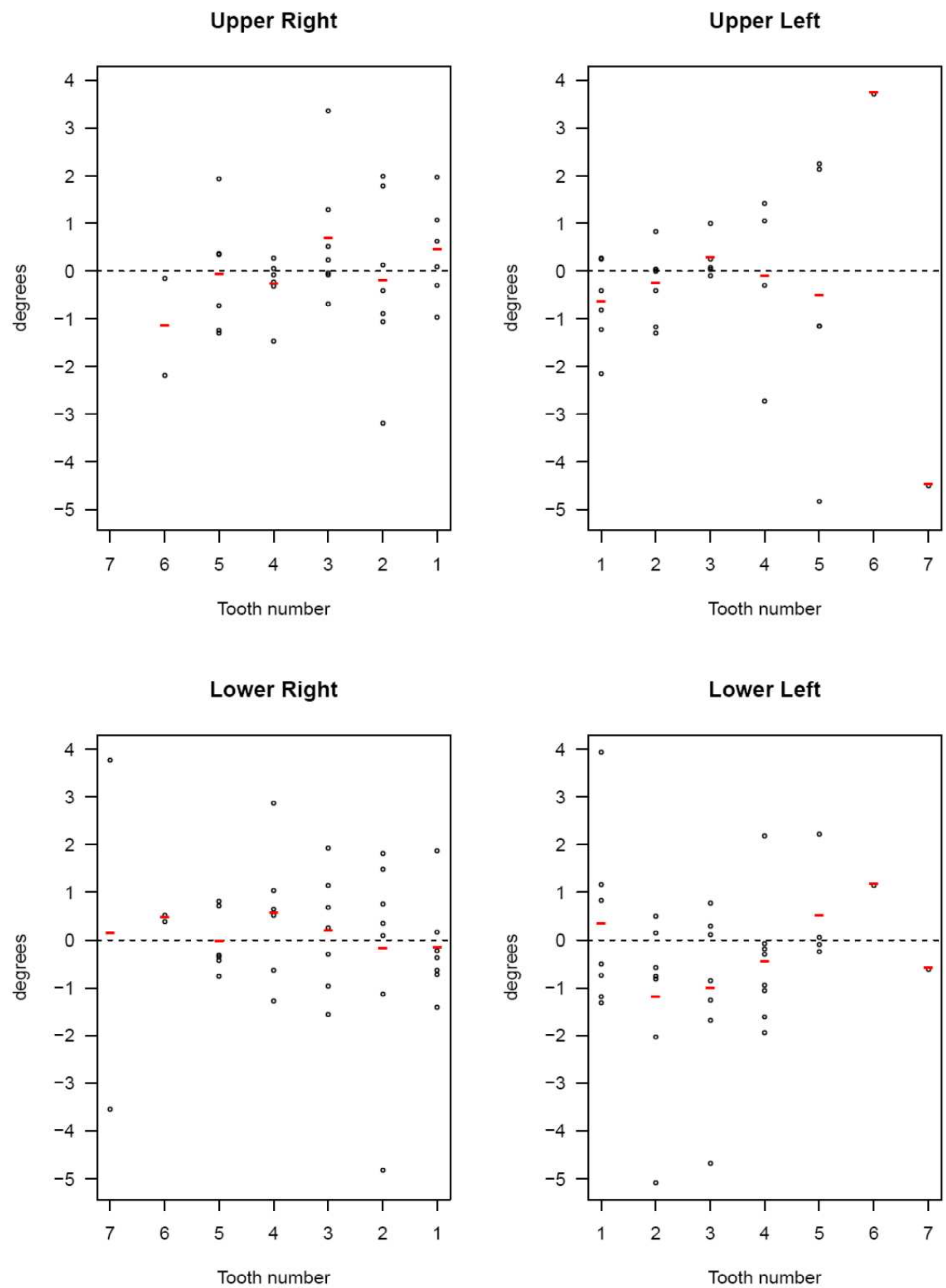
Subject 3 LR4 measurement was removed because it was an outlier. 3 measurements were also removed due to software error.Tooth means are denoted by a red −.

Appendix Ic: Vertical Data Plot



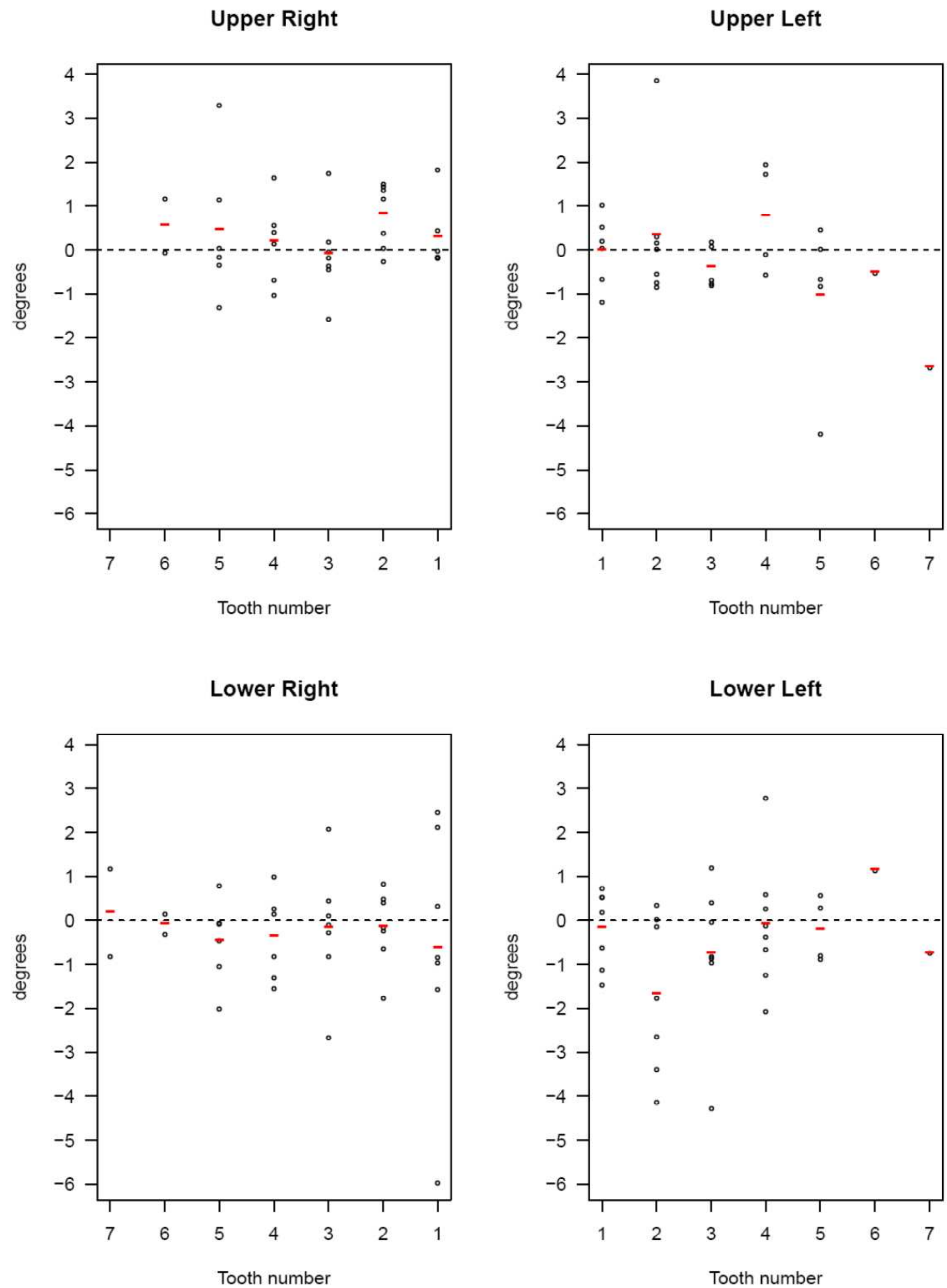
Subject 3 LR4 measurement was removed because it was an outlier. 3 measurements were also removed due to software error.Tooth means are denoted by a red −.

Appendix Id: Torque Data Plot



Subject 3 LR4 measurement was removed because it was an outlier. 3 measurements were also removed due to software error.Tooth means are denoted by a red −.

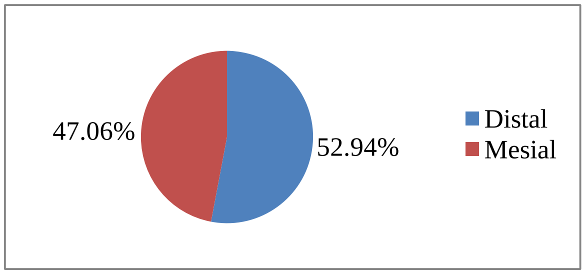
Appendix Ie: Tip Data Plot



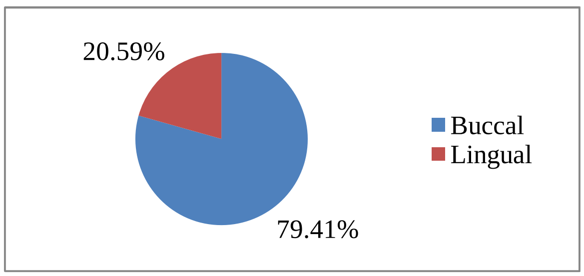
Subject 3 LR4 measurement was removed because it was an outlier. 3 measurements were also removed due to software error.Tooth means are denoted by a red −.

Appendix If: Rotation Data Plot

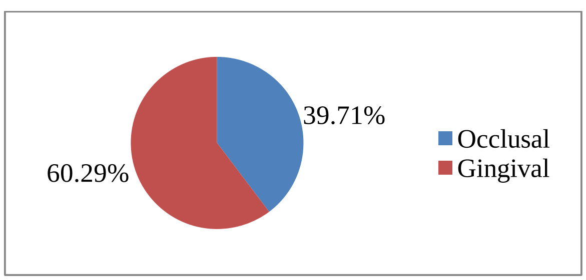
Appendix II: Frequency of Directional Bias



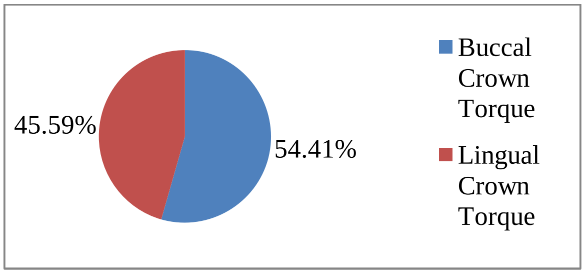
Appendix IIa: Mesial-Distal Directional Bias



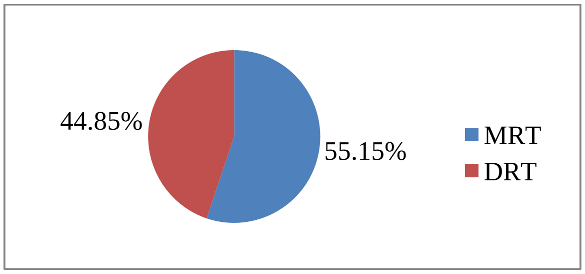
Appendix IIb: Buccal-Lingual Directional Bias



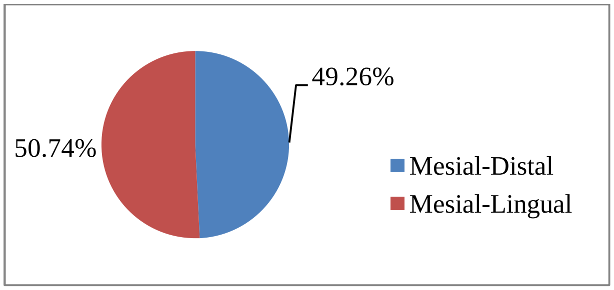
Appendix IIc: Vertical Directional Bias



Appendix IId: Torque Directional Bias

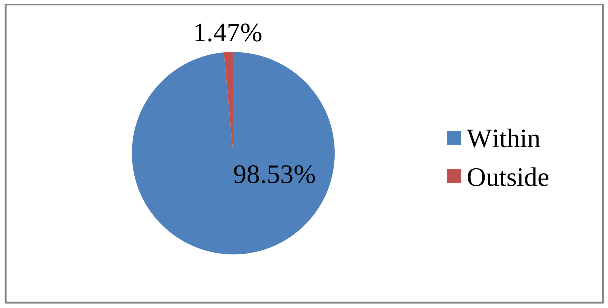


Appendix IIe: Tip Directional Bias

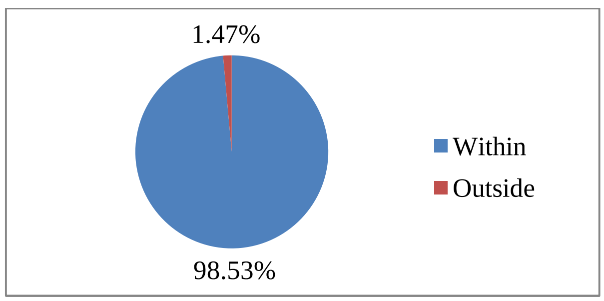


Appendix IIf: Rotation Directional Bias

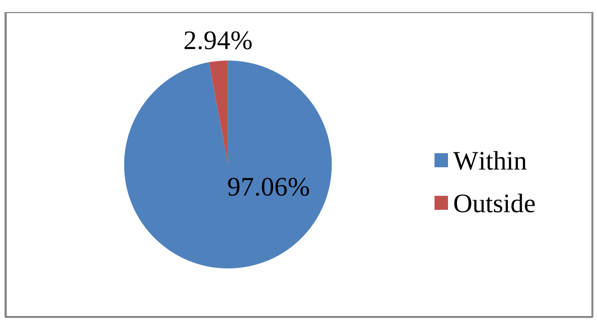
Appendix III: Frequency of Bracket Positioning within Acceptable Range



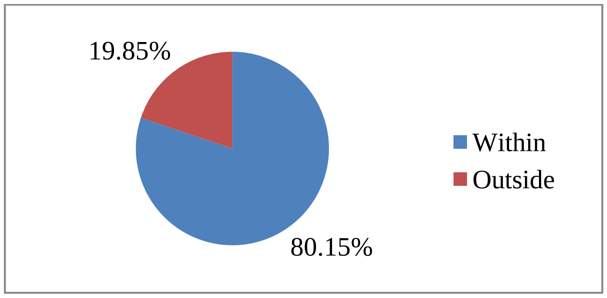
Appendix IIIa: Mesial-Distal Positioning within Acceptable Range



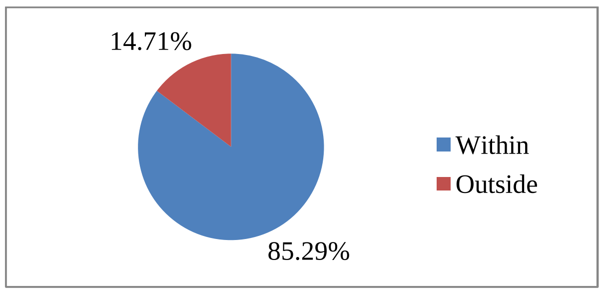
Appendix IIIb: Buccal-Lingual Positioning within Acceptable Range



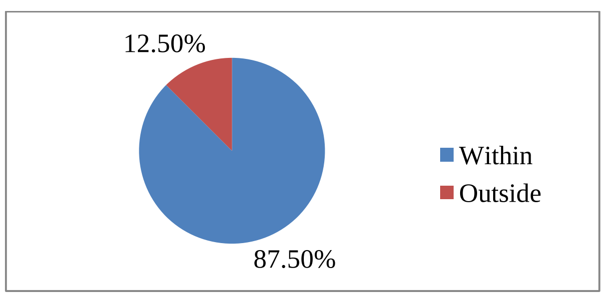
Appendix IIIc: Vertical Positioning within Acceptable Range



Appendix IIId: Torque Positioning within Acceptable Range

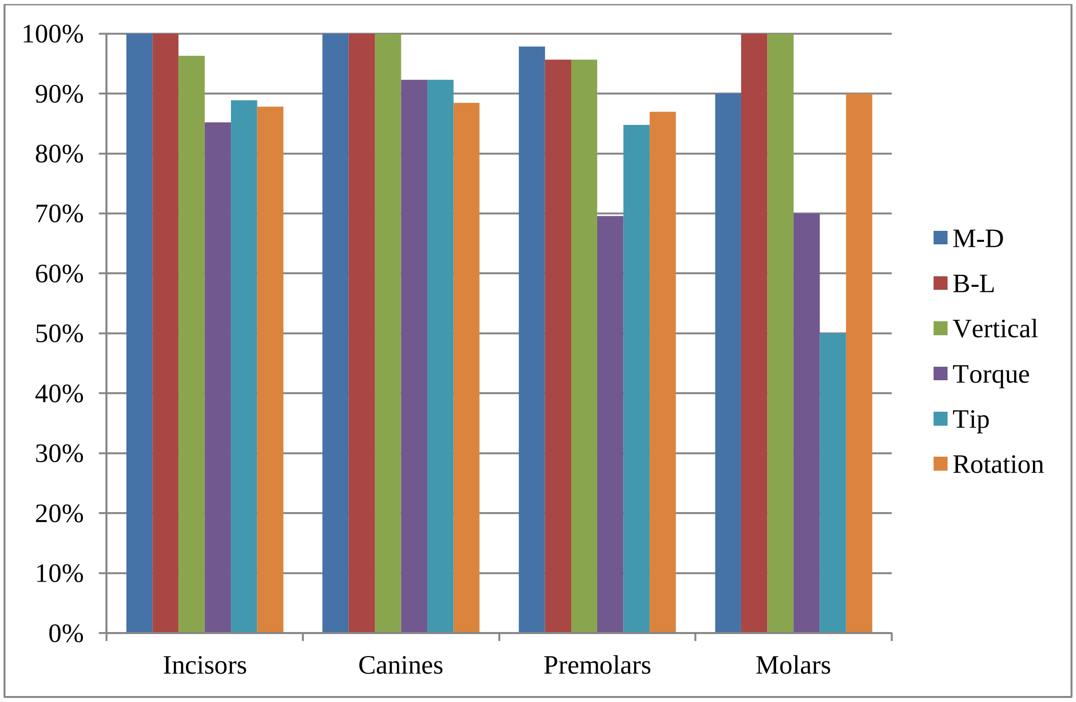


Appendix IIIe: Tip Positioning within Acceptable Range



Appendix IIIf: Rotation Positioning within Acceptable Range

Appendix IV: Percentage within Acceptable Range by Tooth Type:



Appendix V: Materials

Modern Materials Die Keen (Green)
Water/Powder Ratio: 21 ml/100 gm
Initial set: 10-13 minutes
Expansion: 0.18-0.2%
18,000 psi

Transbond XT– light cured adhesive
3M Unitek
Saint Paul, MN USA

Maxcure – acid-base adhesive sealant
Reliance Orthodontic Products
Itasca, IL USA

3M ESPE Express STD
Firmer Set
Vinyl polysiloxane impression material putty
ISO 4823 Type O
Max Comp. Set <1.0%
Recovery from deformation >99.0%
Max Dimensional Change: 24hrs - <0.3%, 2 weeks - <0.3%