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Accuracy and Reliability of a New Methodology to Monitor Root Movement in Three Dimensions During Orthodontic Treatment

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Accuracy and Reliability of a New Methodology to Monitor Root Movement in Three Dimensions During Orthodontic Treatment

by

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THESIS

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Accuracy and Reliability of a New Methodology to Monitor Root Movement in Three Dimensions During Orthodontic Treatment

Robert Lee

ABSTRACT

INTRODUCTION: Current methods to evaluate root position are either inaccurate (panoramic radiograph) or expose patients to relatively large amounts of radiation (CBCT). A method to evaluate root position by generating an expected root position (ERP) setup was recently reported but has not been validated. The purpose of this study was to quantitatively assess the accuracy and reliability of the ERP setup with adequate statistical power.

METHODS: This retrospective study included fifteen subjects who had completed phase II orthodontic treatment. An ERP setup was generated for all patients at post-treatment. The ERP setup was compared to the post-treatment CBCT scan which served as the control. The mesiodistal angulation and buccolingual inclination of all teeth in both the ERP setup and post-treatment CBCT scan were measured and compared. Bland-Altman analysis was used to assess inter-operator reliability, intra-operator reliability, and the agreement between the ERP setup and post-treatment CBCT scan.

RESULTS: Bland-Altman plots found high inter-operator and intra-operator reliability. Bland-Altman plots also showed strong agreement between the ERP setup and post-treatment CBCT scan. 11.8% of teeth measured for mesiodistal angulation and 9.6% of teeth measured for buccolingual inclination were outside of the ±2.5° range of clinical acceptability.

CONCLUSIONS: We have validated that the method to generate an ERP setup to evaluate root position during orthodontic treatment is accurate and reliable.

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INTRODUCTION

The objective of orthodontic treatment is to ideally position teeth (crown and root) into a stable, esthetic, and functional occlusion. The guidelines orthodontists often follow to achieve this optimal occlusion are Andrews' 6 keys to normal occlusion.[1] Of Andrews' six keys, four of his keys (molar relationship, rotations, spaces, and occlusal plane) depend solely on crown position. Andrews' other two keys (mesiodistal angulation and buccolingual inclination) depend on both crown and root position due to variations in crown morphologies, inconsistencies in crown-root angulations, and short crown length relative to root length.[2–7]

Achieving satisfactory root position during orthodontic treatment is essential for optimal restorative treatment, periodontal health, and occlusal function. Previous reports have demonstrated that restorative or periodontal treatment may be compromised if roots of adjacent teeth are positioned in too close proximity to one another.[8,9] Root proximity in which the adjacent roots are apart by 1.0mm or less has been shown to result in poorly shaped gingival embrasures, jeopardized health of the interproximal space, horizontal bone loss, and more rapid periodontal breakdown.[10–15] In addition, accurate root placement and parallelism are important to produce proper occlusal and incisal function and to distribute occlusal forces.[2,16]

Root position during orthodontic treatment is evaluated through x-rays, most commonly seen in the form of a panoramic radiograph. A 2008 *Journal of Clinical Orthodontics (JCO)* survey of American orthodontists reported that 67.4% of respondents took progress panoramic radiographs and 80.1% of respondents took post-treatment panoramic radiographs to monitor and finalize root position.[17] However, panoramic radiographs are not ideal for evaluating root position since previous studies have determined that they are inaccurate in depicting root position because of distortions and projection effects due to the nonorthogonal x-ray beams directed at the teeth.[18–

[21] In addition, prior studies have reported that radiographic techniques should be able to evaluate root angulations within an accuracy of 2.5° in either direction to be considered clinically acceptable, yet panoramic radiographs depict 53-73% of root angulations outside of this clinically acceptable range.[19–22]

Cone-beam computed tomography (CBCT) is another radiographic technique that is used to assess root position during orthodontic treatment. In contrast with panoramic radiographs, CBCT scans have been reported to accurately evaluate root positions in three dimensions and depict dentofacial structures in a 1:1 ratio.[18,23–26] However, compared to panoramic radiographs, CBCT scans expose patients to higher levels of radiation, so multiple CBCT scans for the purpose of evaluating root position may not be clinically recommended, especially in children.[25–27] While CBCT technology continues to improve by decreasing the radiation exposure to patients, practitioners are always recommended to follow the As Low as Reasonably Achievable (ALARA) principle and minimize exposing patients to radiation whenever possible.[28] Therefore, a technique that can accurately evaluate root position in three dimensions while also minimizing radiation exposure to patients is desirable.

A new methodology that generates an "expected root position" (ERP) setup was recently demonstrated to have the potential to evaluate root position at any stage of orthodontic treatment by combining a single pre-treatment CBCT scan with digital scans of teeth.[29–31] This generated ERP setup is an approximation of the root position at a specific orthodontic stage of interest and has been demonstrated in an ex-vivo typodont model, clinically in one subject at post-treatment, and through a five patient post-treatment pilot study.[29–31] Quantitative analysis of this approach with adequate statistical power and with reliability testing was not performed in these previous studies. Thus, the purpose of the present study was to quantitatively assess the accuracy and reliability of the ERP setup in a larger sample size with adequate statistical power.

MATERIALS AND METHODS

This retrospective study was approved (approval # 10-00564) by the Committee on Human Research (CHR) at the University of California, San Francisco (UCSF). Records for this study were obtained from the patient database of the UCSF Division of Orthodontics. The inclusion criteria for this study were subjects who had completed Phase II orthodontic treatment and whose records consisted of pre-treatment and post-treatment study models and CBCT scans. The exclusion criteria for this study were patients who had extensive restorations covering more than two surfaces or who had restorations performed during orthodontic treatment. The exclusion criteria also excluded teeth with dilacerated roots and patients with poor CBCT scan resolution. Based on the previously reported pilot study on this methodology that determined the number of patients needed for adequate statistical power, we selected fifteen patients meeting the inclusion and exclusion criteria using convenience sampling.[31]

The Anatomodel 3D modeling service (Anatomage, San Jose, CA) was used to generate all segmentations of teeth from pre-treatment and post-treatment CBCT scans. An Ortho Insight (MotionView Software, LLC, Hixson, TN) extra-oral laser scanner was used to scan all post-treatment study models. The Ortho Insight software was used to segment, individualize, and export as PLY files the laser scanned post-treatment crowns. To generate the ERP setup at post-treatment, the individualized pre-treatment CBCT teeth obtained from Anatomodel were superimposed using 3-matic software (version 9.0; Materialise, Leuven, Belgium) onto their respective individualized post-treatment laser scanned crowns (Fig 1). The superimposition was first roughly approximated using an N points registration function in which three matching points were selected on each pre-treatment CBCT tooth and its respective post-treatment laser scanned crown. Gross errors in mesiodistal angulation and buccolingual inclination after N points registration were then corrected using the operator's best judgment to match the alignment of the long axes of the pre-treatment CBCT teeth and post-treatment laser scanned crowns through rotation and translation functions. The last step in the superimposition process was to use a global registration function which applied an iterative closest point algorithm.

To quantitatively assess the ERP setup and post-treatment CBCT scan, the mesiodistal angulations and buccolingual inclinations were measured for all teeth in both the ERP setup and the post-treatment CBCT scan. To measure the teeth in the ERP setup, the surface contour of the ERP setup was overlaid onto the CBCT scan in Mimics software (version 16.0; Materialise, Leuven, Belgium). The contrast on the CBCT scan was adjusted to create a black background in order to minimize bias in measurements from the CBCT scan. To find the mesiodistal angulation and buccolingual inclination, the long axis of the tooth was first determined by selecting points for the center of the crown and root in all three dimensions.[32,33] The point chosen for the center of the molar roots often end up in the furcation area. A point directly mesial to the center of the crown point was chosen for the mesiodistal angulation measurement. A point directly lingual to the center of the crown point was chosen for the buccolingual inclination measurement. Using the three points chosen from the long axis and the mesial or lingual points, the mesiodistal angulation and buccolingual inclination were measured for all teeth (Fig 2). The mesiodistal angulation and buccolingual inclination of each tooth was measured five times, and the mean of these five measurements was later used for further analysis. The post-treatment CBCT scan, which served as the control, applied the same methodology for measuring mesiodistal angulation and buccolingual inclination (Fig 3).

Two operators collected the ERP setup and post-treatment CBCT scan mesiodistal angulation and buccolingual inclination measurements for all subjects. Each operator repeated their measurements at a minimum of one week later yielding a total of four sets of measurements for each subject. The two operators were blinded on which subject they were measuring at all times.

Statistical Analysis

To determine the agreement between the mesiodistal angulation and buccolingual inclination measurements of the ERP setup and post-treatment CBCT scan, the Bland-Altman method was used.[34–36] Inter-operator and intra-operator reliability were also assessed using the Bland-Altman method.

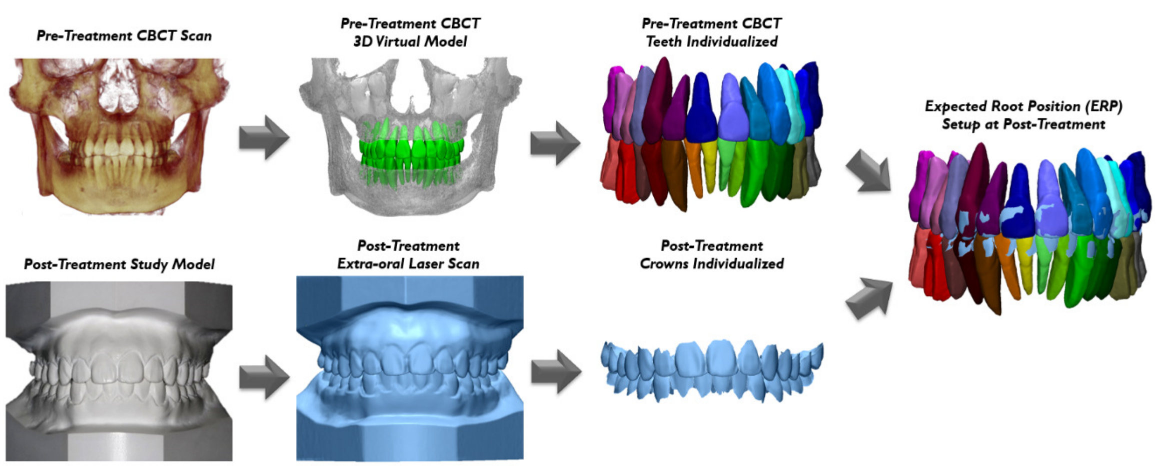

Figure 1. Methodology to generate an ERP setup at post-treatment. The teeth from the pre-treatment CBCT scan are segmented and individualized. A study model at the orthodontic stage of interest, in this case at post-treatment, is scanned with an extra-oral laser scanner. The individualized pre-treatment CBCT teeth are superimposed onto the post-treatment extra-oral laser scanned crowns yielding the ERP setup.

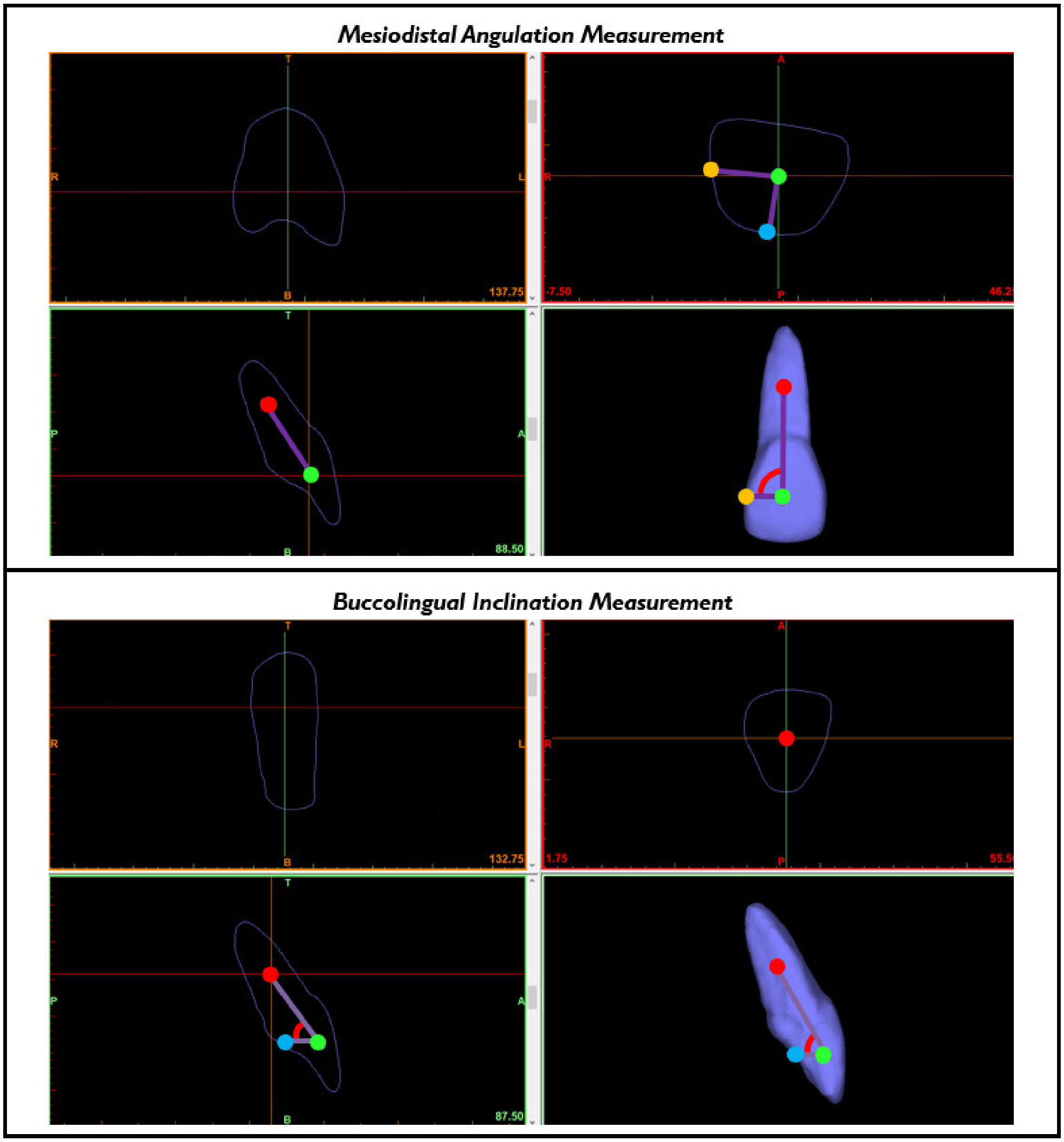

Figure 2. Method to measure the mesiodistal angulation and buccolingual inclination of an incisor for the ERP setup. The long axis was determined by choosing the center of the crown (green point) and root (red point). For mesiodistal angulation, a point (orange point) directly mesial of the crown point was chosen. For buccolingual inclination, a point (blue point) directly lingual to the crown point was chosen.

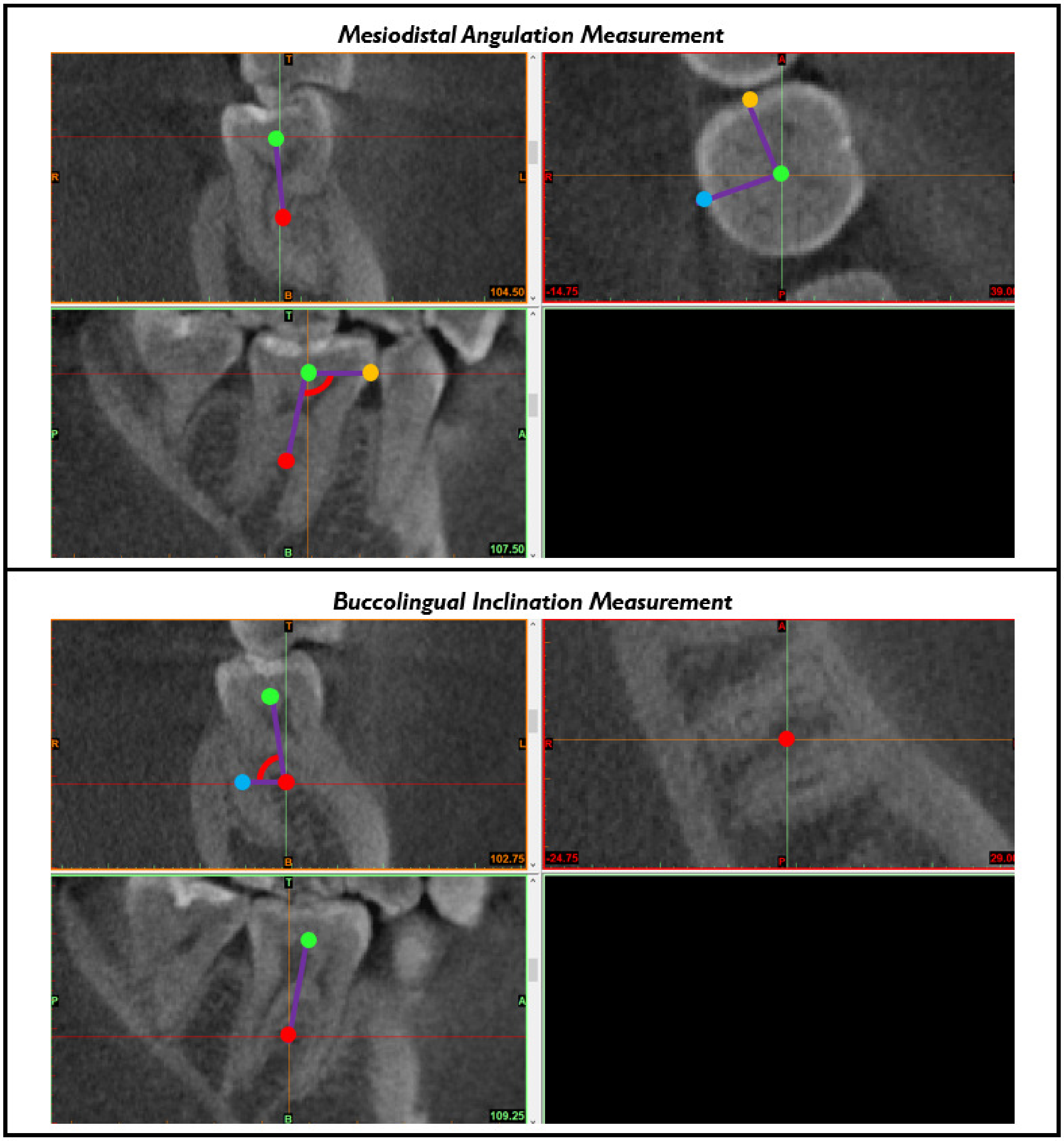

Figure 3. Method to measure the mesiodistal angulation and buccolingual inclination of a molar for the post-treatment CBCT scan. The long axis was determined by choosing the center of the crown (green point) and root (red point). For mesiodistal angulation, a point (orange point) directly mesial of the crown point was chosen. For buccolingual inclination, a point (blue point) directly lingual to the crown point was chosen.

RESULTS

For the precision of data collection within operators, intra-operator reliability was tested for both the post-treatment CBCT scan and ERP setup. For each operator, their first and second set of measurements for the post-treatment CBCT scan were compared as well as their first and second set of measurements for the ERP setup. The intra-operator agreement results, which were assessed using the Bland-Altman method, are shown in Table 1. The Bland-Altman plots for both operator's (Fig 4) demonstrate strong agreement for both operators for all measurements.

Table 1. Bland-Altman analysis for intra-operator reliability

	Bias (°)	*Lower limit of agreement (°)*	*Upper limit of agreement (°)*	*Limit of agreement interval width (°)*
Mesiodistal Angulation				
Operator 1 Post-Treatment CBCT	0.176	-2.089	2.441	4.53
Operator 2 Post-Treatment CBCT	0.152	-1.624	1.927	3.551
Operator 1 ERP Setup	-0.076	-2.009	1.856	3.865
Operator 2 ERP Setup	-0.043	-2.339	2.254	4.4879
Buccolingual Inclination				
Operator 1 Post-Treatment CBCT	-0.071	-2.743	2.601	5.344
Operator 2 Post-Treatment CBCT	-0.021	-2.111	2.069	4.18
Operator 1 ERP Setup	-0.022	-2.029	1.985	4.014
Operator 2 ERP Setup	-0.198	-2.242	1.846	4.088

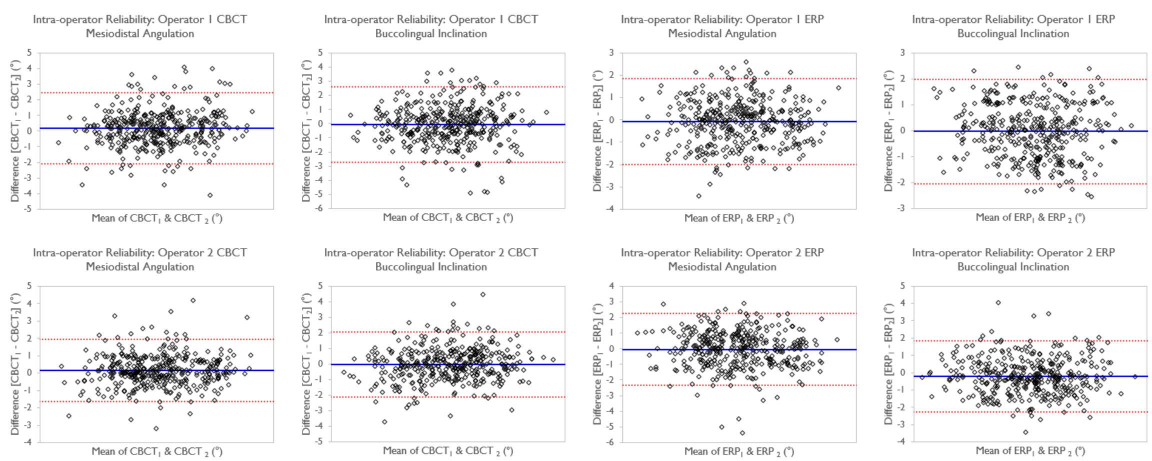

Figure 4. Bland-Altman plots for intra-operator reliability testing of measurements made within each operator's two sets of post-treatment CBCT and ERP setup measurements. The top row shows operator 1's intra-operator reliability and the bottom row shows operator 2's intra-operator reliability. For each plot, the x-axis represents the mean of the compared measurements, and the y-axis represents the difference between the compared measurements. The blue line represents the bias and the red hashed lines represent the upper and lower limits of agreement. All measurements are in degrees.

For the precision of data collection between operators, inter-operator reliability was tested for both the post-treatment CBCT scan and ERP setup. Between each operator, the first set of measurements for the post-treatment CBCT scan were compared against each other as well as the first set of measurements for the ERP setup. This process was repeated between the operators' second set of measurements. The inter-operator agreement results, which were assessed using the Bland-Altman method, are shown in Table 2. The Bland-Altman plots between both operator's two sets of measurements (Fig 5) demonstrate strong agreement between all operator measurements.

Table 2. Bland-Altman analysis for inter-operator reliability

	Bias (°)	Lower limit of agreement (°)	Upper limit of agreement (°)	Limit of agreement interval width (°)
Mesiodistal Angulation				
Set 1 Post-Treatment CBCT	-0.322	-2.637	1.993	4.630
Set 2 Post-Treatment CBCT	-0.290	-2.928	2.348	5.276
Set 1 ERP Setup	-0.334	-2.817	2.151	4.968
Set 2 ERP Setup	-0.328	-3.442	2.786	6.228
Buccolingual Inclination				
Set 1 Post-Treatment CBCT	0.042	-2.375	2.460	4.835
Set 2 Post-Treatment CBCT	0.001	-2.993	2.994	5.987
Set 1 ERP Setup	0.352	-2.089	2.794	4.883
Set 2 ERP Setup	0.529	-2.398	3.456	5.854

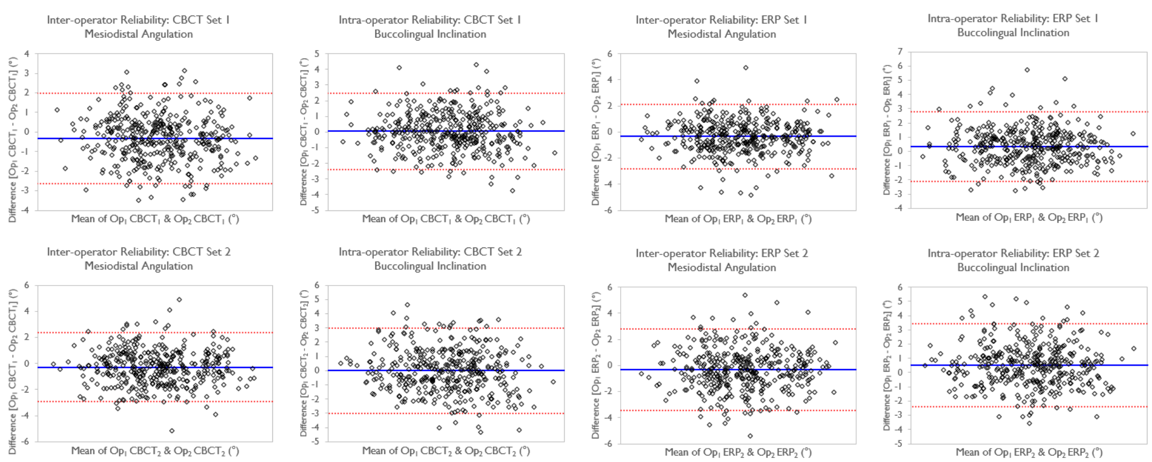

Figure 5. Bland-Altman plots for inter-operator reliability testing of measurements made between operators post-treatment CBCT and ERP setup measurements. The top row shows the inter-operator reliability for the two operators' first set of measurements and the bottom row shows the inter-operator reliability for the two operators' second set of measurements. For each plot, the x-axis represents the mean of the compared measurements, and the y-axis represents the difference between the compared measurements. The blue line represents the bias and the red hashed lines represent the upper and lower limits of agreement. All measurements are in degrees.

To assess the accuracy of the ERP setup in evaluating root position, the agreement between the ERP setup and post-treatment CBCT scan was compared. Table 3 and 4 show the agreement between operator 1's first set of ERP setup and post-treatment CBCT scan measurements for mesiodistal angulation and buccolingual inclination respectively. The Bland-Altman plots for operator 1's first set of measurements for mesiodistal angulation (Fig 6) and buccolingual inclination (Fig 7) demonstrate strong agreement for all tooth types with few outliers outside of the limits of agreement.

Table 3. Bland-Altman analysis between operator 1's first set of post-treatment CBCT scan and ERP Setup mesiodistal angulation measurements

Tooth Type	*Bias (°)*	*Lower limit of agreement (°)*	*Upper limit of agreement (°)*	*Limit of agreement interval width (°)*
Mx Molars	0.331	-2.473	3.135	5.608
Mx Premolars	-0.472	-3.730	2.785	6.515
Mx Canines	0.365	-2.265	2.994	5.259
Mx Incisors	0.354	-2.485	3.193	5.678
Mn Molars	0.745	-2.063	3.552	5.615
Mn Premolars	-0.052	-3.737	3.633	7.370
Mn Canines	0.577	-2.313	3.466	5.779
Mn Incisors	0.370	-2.842	3.583	6.425

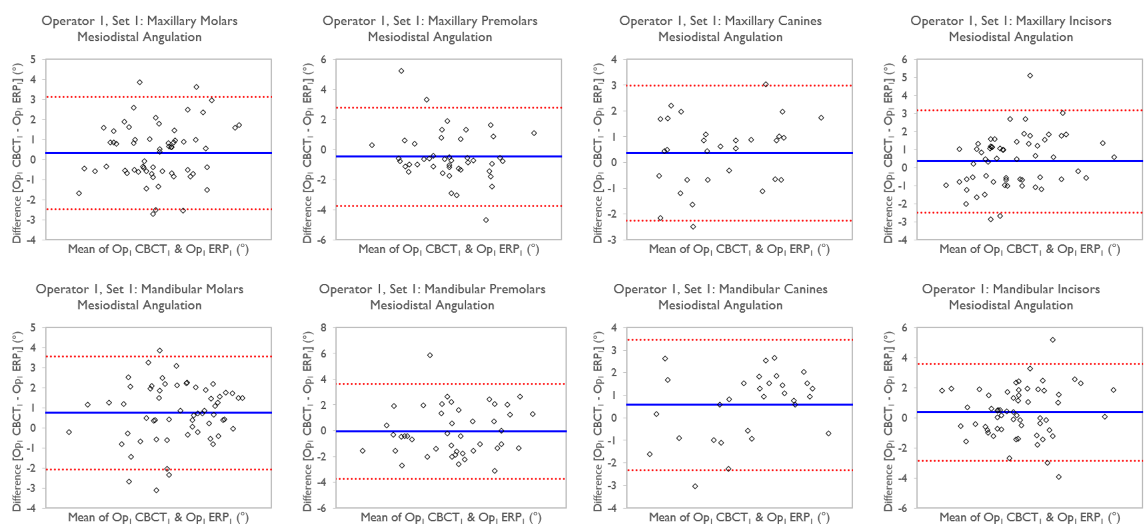

Figure 6. Bland-Altman plots between operator 1's first set of post-treatment CBCT scan and ERP setup mesiodistal angulation measurements stratified by tooth type. For each plot, the x-axis represents the mean of the compared measurements, and the y-axis represents the difference between the compared measurements. The blue line represents the bias and the red hashed lines represent the upper and lower limits of agreement. All measurements are in degrees.

Table 4. Bland-Altman analysis between operator 1's first set of post-treatment CBCT scan and ERP Setup buccolingual inclination measurements

Tooth Type	*Bias (°)*	*Lower limit of agreement (°)*	*Upper limit of agreement (°)*	*Limit of agreement interval width (°)*
Mx Molars	0.604	-1.996	3.204	5.200
Mx Premolars	-0.005	-2.803	2.794	5.597
Mx Canines	-0.044	-2.934	2.846	5.780
Mx Incisors	0.391	-2.484	3.266	5.750
Mn Molars	-0.037	-3.092	3.019	6.111
Mn Premolars	0.475	-2.574	3.523	6.097
Mn Canines	0.245	-2.607	3.098	5.705
Mn Incisors	0.022	-3.061	3.105	6.166

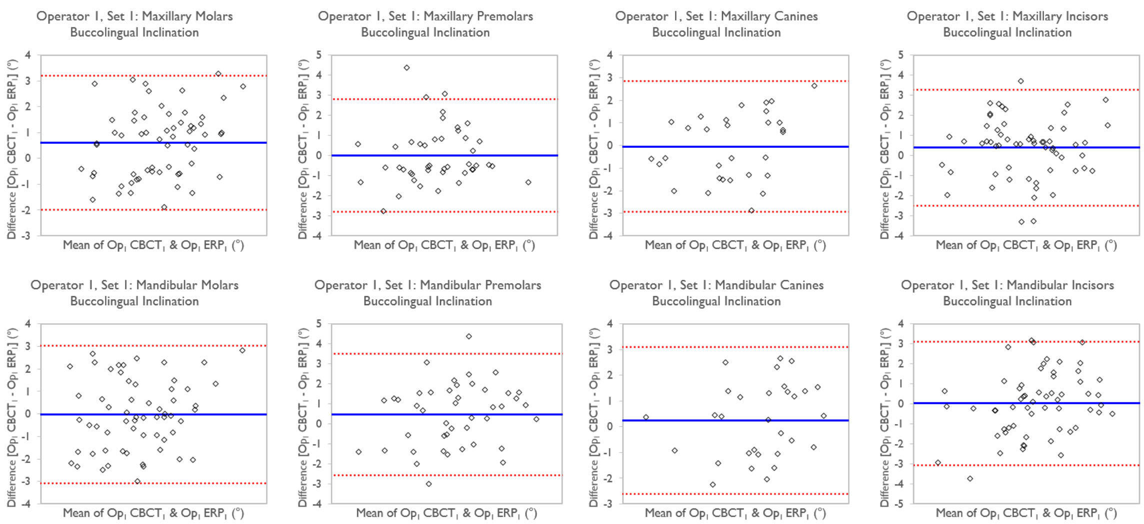

Figure 7. Bland-Altman plots between operator 1's first set of post-treatment CBCT scan and ERP setup buccolingual inclination measurements stratified by tooth type. For each plot, the x-axis represents the mean of the compared measurements, and the y-axis represents the difference between the compared measurements. The blue line represents the bias and the red hashed lines represent the upper and lower limits of agreement. All measurements are in degrees.

The percentage of difference in measurements between the ERP setup and post-treatment CBCT scan that fell outside of the ±2.5° clinically acceptable range was reported in Table 5 for mesiodistal angulation and Table 6 for buccolingual inclination for all four sets of measurements completed by the two operators. For mesiodistal angulation, 11.8% (182/1548) of measurements fell outside of ±2.5°clinically acceptable range while for buccolingual inclination 9.6% (148/1548) of measurements fell outside of the ±2.5° clinically acceptable range. The mean and standard deviation after taking the absolute value of the difference between the ERP setup and post-treatment CBCT scan measurements are shown in Table 7 for mesiodistal angulation and Table 8 for buccolingual inclination. The total mean difference of all measurements for mesiodistal angulation was 1.39° ± 1.05° and for buccolingual inclination was 1.30° ± 0.92° which falls within the ±2.5° clinically acceptable range.

Table 5. Percentage of mesiodistal angulation measurements outside of ±2.5° clinically acceptable range

Tooth Type	*Operator 1 Set 1*	*Operator 1 Set 2*	*Operator 2 Set 1*	*Operator 2 Set 2*	*Total*
Mx Molars	7/60 = 11.7%	4/60 = 6.7%	6/60 = 10.0%	8/60 = 13.3%	25/240 = 10.4%
Mx Premolars	5/44 = 11.4%	6/44 = 13.6%	7/44 = 15.9%	5/44 = 11.4%	23/176 = 13.1%
Mx Canines	2/30 = 6.7%	4/30 = 13.3%	4/30 = 13.3%	3/30 = 10.0%	13/120 = 10.8%
Mx Incisors	6/60 = 10.0%	7/60 = 11.7%	7/60 = 11.7%	5/60 = 8.3%	25/240 = 10.4%
Mn Molars	5/60 = 8.3%	8/60 = 13.3%	6/60 = 10.0%	7/60 = 11.7%	26/240 = 10.8%
Mn Premolars	6/44 = 13.6%	7/44 =15.9%	5/44 = 11.4%	7/44 = 15.9%	25/176 = 14.2%
Mn Canines	4/30 = 13.3%	4/30 = 13.3%	6/30 = 20.0%	5/30 = 16.7%	19/120 = 15.8%
Mn Incisors	6/59 = 10.2%	7/59 = 11.9%	8/59 = 13.6%	5/59 = 8.5%	26/236= 11.0%
Total	41/387 = 10.6%	47/387 = 12.1%	49/387 = 12.7%	45/387 = 11.6%	182/1548 = 11.8%

Table 6. Percentage of buccolingual inclination measurements outside of ±2.5° clinically acceptable range

Tooth Type	*Operator 1 Set 1*	*Operator 1 Set 2*	*Operator 2 Set 1*	*Operator 2 Set 2*	*Total*
Mx Molars	7/60 = 11.7%	4/60 = 6.7%	5/60 = 8.3%	7/60 = 11.7%	23/240 = 9.6%
Mx Premolars	4/44 = 9.1%	5/44 = 11.4%	4/44 = 9.1%	3/44 = 6.8%	16/176 = 9.1%
Mx Canines	2/30 = 6.7%	3/30 = 10.0%	2/30 = 6.7%	4/30 = 13.3%	11/120 = 9.2%
Mx Incisors	7/60 = 11.7%	5/60 = 8.3%	8/60 = 13.3%	8/60 = 13.3%	28/240 = 11.7%
Mn Molars	3/60 = 5.0%	4/60 = 6.7%	5/60 = 8.3%	5/60 = 8.3%	17/240 = 7.1%
Mn Premolars	4/44 = 9.1%	3/30 = 10.0%	4/44 = 9.1%	6/44 = 13.6%	17/176 = 9.7%
Mn Canines	3/30 = 10.0%	5/30 = 16.7%	3/30 = 10.0%	4/30 = 13.3%	15/120 = 12.5%
Mn Incisors	7/59 = 11.9%	3/59 = 5.1%	4/59 = 6.8%	7/59 = 11.9%	21/236 = 8.9%
Total	37/387 = 9.6%	32/387 = 8.3%	35/387 = 9.0%	44/387 = 11.4%	148/1548 = 9.6%

Table 6. Percentage of buccolingual inclination measurements outside of ±2.5° clinically acceptable range

Tooth Type	*Operator 1 Set 1*	*Operator 1 Set 2*	*Operator 2 Set 1*	*Operator 2 Set 2*	*Total*
Mx Molars	7/60 = 11.7%	4/60 = 6.7%	5/60 = 8.3%	7/60 = 11.7%	23/240 = 9.6%
Mx Premolars	4/44 = 9.1%	5/44 = 11.4%	4/44 = 9.1%	3/44 = 6.8%	16/176 = 9.1%
Mx Canines	2/30 = 6.7%	3/30 = 10.0%	2/30 = 6.7%	4/30 = 13.3%	11/120 = 9.2%
Mx Incisors	7/60 = 11.7%	5/60 = 8.3%	8/60 = 13.3%	8/60 = 13.3%	28/240 = 11.7%
Mn Molars	3/60 = 5.0%	4/60 = 6.7%	5/60 = 8.3%	5/60 = 8.3%	17/240 = 7.1%
Mn Premolars	4/44 = 9.1%	3/30 = 10.0%	4/44 = 9.1%	6/44 = 13.6%	17/176 = 9.7%
Mn Canines	3/30 = 10.0%	5/30 = 16.7%	3/30 = 10.0%	4/30 = 13.3%	15/120 = 12.5%
Mn Incisors	7/59 = 11.9%	3/59 = 5.1%	4/59 = 6.8%	7/59 = 11.9%	21/236 = 8.9%
Total	37/387 = 9.6%	32/387 = 8.3%	35/387 = 9.0%	44/387 = 11.4%	148/1548 = 9.6%

Table 8. Mean difference of buccolingual inclination measurements

Tooth Type	*Operator 1 Set 1*	*Operator 1 Set 2*	*Operator 2 Set 1*	*Operator 2 Set 2*	*Total*
Mx Molars	1.23° ± 0.76°	1.31° ± 0.93°	1.25° ± 0.85°	1.41° ± 1.17°	1.30° ± 0.94°
Mx Premolars	1.13° ± 0.85°	1.32° ± 1.24°	1.16° ± 1.04°	1.46° ± 0.95°	1.27° ± 1.03°
Mx Canines	1.31° ± 0.64°	1.22° ± 0.69°	1.26° ± 0.78°	1.50° ± 1.00°	1.32° ± 0.79°
Mx Incisors	1.24° ± 0.87°	1.23° ± 0.96°	1.34° ± 1.04°	1.48° ± 0.98°	1.32° ± 0.96°
Mn Molars	1.28° ± 0.88°	1.19° ± 0.77°	1.23° ± 0.88°	1.44° ± 0.94°	1.28° ± 0.87°
Mn Premolars	1.37° ± 0.86°	1.23° ± 0.90°	1.15° ± 0.89°	1.41° ± 1.22°	1.29° ± 0.97°
Mn Canines	1.28° ± 0.70°	1.36° ± 0.83°	1.13° ± 0.89°	1.52° ± 1.04°	1.32° ± 0.88°
Mn Incisors	1.23° ± 0.96°	1.36° ± 0.68°	1.30° ± 0.87°	1.41° ± 0.95°	1.33° ± 0.87°
Total	1.25° ± 0.83°	1.28° ± 0.89°	1.24° ± 0.91°	1.45 ± 1.03°	1.30° ± 0.92°

DISCUSSION

Proper root position and parallelism are necessary for successful orthodontic treatment. An index to evaluate the success of orthodontic treatment is the American Board of Orthodontics (ABO) grading system which recommends proper root position and deducts points if the adjacent roots are not generally parallel with each other.[37] The ABO recommends evaluation of root angulation using panoramic radiographs even though they also acknowledge that distortions often occur with panoramic radiographs resulting in inaccurate portrayal of root angulations. While CBCT scans have the capability to accurately depict root position, CBCT scans expose patients to higher levels of radiation than panoramic radiographs, so multiple CBCT scans for the purpose of monitoring root position during orthodontic treatment may not be clinically recommended. Therefore, a new methodology that generates an ERP setup was developed to have the capability to evaluate root position at any stage of orthodontic treatment with minimal radiation. However, this approach has not been validated in a larger population with adequate statistical power. A previous pilot study demonstrated that 15 subjects would be needed to validate this methodology with adequate statistical power.[31]

Measurement of the mesiodistal angulation and buccolingual inclination from the post-treatment CBCT scan and ERP setup was used to compare these imaging techniques. The method reported in this study to measure the mesiodistal angulation and buccolingual inclination does not use the traditional points chosen for these two measurements. This study only needed to find the difference between the mesiodistal angulation and buccolingual inclination of the teeth from the post-treatment CBCT scan and ERP setup rather than the true measurements of them. Thus, as long as the method to measure the mesiodistal angulation and buccolingual inclination for both the

CBCT scan and ERP setup are the same and consistent, then the difference will be accurately reflected between these two sets of measurements.

During pre-testing of this method to measure the mesiodistal angulation and buccolingual inclination, some variability was found between the two operators and within the same operator when making the same measurement. To account for the variability in the measurements due to operator error, the number of measurements taken for each tooth was sequentially increased until the mean of the measurements between and within operators became more similar which was determined to be five measurements. The mean of these five measurements was then used for the Bland-Altman analysis.

These measurements were performed for all subjects by two operators in order to assess the inter-operator reliability of performing these measurements. These two operators repeated their measurements a minimum of one week later in order to assess the intra-operator reliability of performing these measurements. Bland-Altman analysis was performed to assess inter-operator and intra-operator reliability in which the bias should ideally be close to zero and the measurements should fall within the upper and lower limits of agreement. All Bland-Altman plots for inter-operator and intra-operator reliability testing had biases that were close to 0 with the majority of points falling within the upper and lower limits of agreement demonstrating that the mesiodistal angulation and buccolingual inclination measurements completed by the two operators were reproducible between and within them. The intra-operator reliability error was found to be lower than the inter-operator reliability error which was consistent with previous reports.[38,39]

Agreement between the ERP setup and post-treatment CBCT scan was also assessed using Bland-Altman analysis stratified by tooth type. Because of the large amount of data and Bland-Altman plots generated for each operator's two sets of measurements and the inter-operator and intra-operator reliability were validated to be precise, only operator 1's first set of measurements are presented in this study. The Bland-Altman plots indicate strong agreement between the ERP setup and post-treatment CBCT scan for all tooth types with biases near zero and a minimal number of outliers falling outside of the limits of agreement.

Previous studies have established that there is a clinical acceptability range of 2.5° in either direction for assessment of root angulations.[19,21] Previous studies have found that 53-73% of root angulations when using panoramic radiographs fall outside of this clinical acceptable range.[19,21] This study found that for the ERP setup 11.8% of teeth for mesiodistal angulation and 9.6% of teeth for buccolingual inclination fell outside of this ±2.5° clinically acceptability range which was significantly better than panoramic radiographs. Additionally, panoramic radiographs cannot evaluate buccolingual root inclination because it is a two-dimensional radiographic technique while the ERP setup is in three dimensions and can monitor buccolingual inclination.

Agreement was relatively strong between the ERP setup and post-treatment CBCT scan, but there were some outliers that fell outside of the limits of agreement with some teeth that were significantly off with measurements greater than 5 degrees off. On closer analysis of the teeth that were not aligned correctly in the ERP setup, the main factors involved were either a poor segmentation of the tooth from the CBCT scan, poor resolution of the crown from the extra-oral laser scanner, or a combination of both. Accurate occlusal anatomy is often especially difficult to achieve with threshold segmentation because the patient is in occlusion. Improved ERP setup accuracy is predicted to occur by having the patient bite into a thin piece of wax during the pre-treatment CBCT scan. The wax would induce a small separation between the upper and lower teeth resulting in easier segmentation of the occlusal anatomy. The accuracy of the extra-oral laser scan also may have played a role. The accuracy of the extra-oral laser scan is dependent on an accurate impression and model pouring process which can be easily distorted. Intra-oral scans may improve the accuracy of the ERP setup because it has a reduced number of steps compared to an extra-oral laser scan. These extra steps when using an extra-oral laser scanner may lead to additional error in the extra-oral laser scanned crowns resulting in decreased accuracy of the ERP setup. Because of the outliers that can occur when generating an ERP setup, practitioners should still use their best clinical judgment when evaluating root position using the ERP setup and be especially critical if the segmentation of the CBCT teeth or resolution of the digital scan is poor.

This study was performed at post-treatment based on the available records at the UCSF Division of Orthodontics. This retrospective study required study models and a CBCT scan to be performed at the same time point which currently only occurs at post-treatment at UCSF. We postulate that this methodology can potentially be performed at any stage in orthodontic treatment that a study model or intra-oral scan is taken and that the bands and brackets would not affect the accuracy or the ERP setup, though a future study at mid-treatment would be needed for validation. Use of this methodology during orthodontic treatment may allow the practitioner to monitor and correct any errors in root position that arise during orthodontic treatment without any further radiation to the patient.

The main limitation of generating an ERP setup is that it is too time consuming to be practical in a clinical setting. However, advancements in CBCT technology, intra-oral scanners, and image-processing software may make this approach feasible for clinical use in the near future. Third party vendors, which were utilized in this study, now have the capability to perform the pre-treatment CBCT scan threshold segmentation which was previously the most time consuming step of this methodology. Intra-oral scanners function through the superimposition of numerous snapshots of the dentition, so potentially in the near future, intra-oral scanners may be able to incorporate the CBCT teeth data and superimpose the roots onto the intra-oral scan in real-time. Other limitations are factors that may decrease the accuracy of generating the ERP setup. Generating an ERP setup relies on accurate crown superimposition of the CBCT teeth onto the digital scan teeth, so any factors that would cause poor segmentation of the CBCT tooth, such as a large restoration, would decrease the accuracy of the crown superimposition. In addition, a restoration to the crown after the pre-treatment CBCT scan, would make the crown anatomy between the pre-treatment CBCT tooth digital scan tooth different resulting in inaccurate crown superimposition.

CONCLUSIONS

1. We have statistically validated that the method to generate an ERP setup to evaluate root position during orthodontic treatment is accurate and reliable.
2. Outliers of root position that fall outside of the limits of agreement when generating an ERP setup can occur if there is a poor segmentation of the CBCT tooth or digital scan crown, so practitioners are recommended to use their best clinical judgment when evaluating root position using the ERP setup.

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