Comparison of movement rate with different initial moment-to-force ratios

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Abstract

Introduction: The objective of this clinical prospective study was to evaluate the effect of the two treatment strategies, translation or controlled tipping followed by root correction, on canine retraction efficiency, specifically canine movement rate.

Methods: Twenty-one patients who needed bilateral maxillary canine retraction to close extraction space as part of their treatment plan were selected for this study. Segmental T-loops designed for controlled tipping or for translation were applied randomly to each side. Two digital maxillary dental casts (taken pre- and post-treatment) were used to measure the tooth displacements of each patient. The coordinate system located at the center of canine crown on the pre-treatment model with the three axes defined in the mesial-distal (M-D), buccal-lingual (B-L), and occlusal-gingival (O-G) directions was used to express the six tooth displacement components. The movement rates on the occlusal plane and in the M-D direction were computed. Movement rates were calculated by dividing the M-D displacements or the resultant displacement on the occlusal plane with the corresponding treatment time.

Results: T-loops for controlled tipping moved canines faster (33.3% on occlusal plane and 38.5% in the M-D direction) than T-loops for translation. The differences are statistically significant ($p = 0.041$ on the occlusal plane and 0.020 in the M-D direction).

Conclusion: 1. Moment-to-force ratio (M/F) impacts on the canine movement rate in a maxillary canine retraction treatment with segmented T-loop mechanism. 2. Within the neighborhood of the ratio for translation, lower M/F moves canine faster than higher M/F both on occlusal plane and in the M-D direction.

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Introduction

Tooth movement rate is one of the most important orthodontic treatment outcomes. It has been commonly used to evaluate effectiveness of treatment strategies and orthodontic appliances. Accurate quantification of the movement rates is critical for the evaluation.

Tooth movement rate has been estimated in previous studies. The relationship between the magnitude of the orthodontic force and tooth movement rate was investigated in animal studies[1–4]. A mathematic model to describe the relationship was also developed based on the experimental studies in beagle dogs.[5] In human studies, movement rates were used to compare the effects of force magnitudes,[6–8] treatment efficiency among different appliances,[9–11] and different types of anchorage.[12] In these studies, tooth movement rate was quantified by using either digital caliper[13–16] or two-dimensional (2D) cephalometric analysis.[17, 18] These methods could only provide linear or 2D measurements between landmarks. The point-to-point measurement did not provide information on tooth movement type, translation and rotation. The off-plane movement and rotations were not assessed. These components are equally important because they characterize the side-effects. Therefore, three-dimensional (3D) tooth movement needs to be quantified.

With the development of 3D imaging and modeling techniques, digital alternatives are available to calculate the 3D tooth movements. The clinical 3D displacements can be calculated using cone-beam computed tomography (CBCT) images.[16] Digital dental casts can also be used to quantify the 3D tooth displacements.[19–23]

Canine retraction after first premolar extraction is a treatment stage of space closure. Two treatment strategies, translation or controlled tipping followed by root correction, are commonly used. Different canine movement patterns (i.e. translation and controlled tipping) were achieved by implementing different treatment strategies characterized by corresponding moment-to-force ratios (M/F).[24] Three-dimensional clinical evaluation has not been reported on the effect of M/F on canine retraction efficiency, specifically canine movement rate, which is the objective of this study.

Materials and Methods

Twenty-one patients (nine male and twelve female) participated in this split-mouth prospective trial study. The study was approved by the Indiana University's Institutional Review Board and signed consent form was documented for each patient. The average age of the patients was 21 ± 8.8 years old. These patients were planned for bilateral maxillary canine retractions (symmetrical pattern) after the upper dental arch was bracketed, leveled, and aligned with sequential archwires to close first pre-molar extraction spaces. Canine roots were radiographically evaluated by the clinician for typical dental anatomy (average root sizes, support and shape). No palatal expansion was performed during the treatment, and no metal or ceramic restorations were on the teeth of interest or their adjacent teeth. All patients were allocated into two groups using the fixed allocation randomization method. Therefore, equal numbers of the canines were treated under either controlled tipping (CT) or translation (TR) strategy. The CT and TR strategies were accomplished by using specifically designed

segmental T-loops, which could provide a distal retraction force of 124 cN along the maxillary arch [25], an anti-tipping and an anti-rotation moment along with minimized force and moment components in other directions.[24] The average desired M/F ratios for 21 patients were 10.69 for TR, and 8.06 for CT. The details of the wire design and orthodontic force verification were reported previously.[24] Patients were scheduled with regular appointments every 5-6 weeks and normally underwent multiple treatment intervals (TIs). A TI was defined as a time interval when the inter-bracket distance between the canine and the 2nd molar on one side reduced over 1 mm. When a TI ended, a pair of new T-loops was re-designed, fabricated, and reactivated consistent with the designated treatment strategies. The study was completed when either CT or TR side finished the canine retraction with the canine in the upright position judged by the clinicians using visual evaluation. Patients' post-treatment Cone beam computed tomography (CBCT) images were used to validate the final positions of the CT side canines.

Two dental casts were used for each patient in this study. The first cast was taken before starting the canine retraction, which was called the pre-treatment cast; and the second one was taken before the last TI started, which was considered as the post-treatment cast. The movements from the last TI were not included because tooth movements might stop sometimes within the period, which was not recorded. The two casts were scanned and digitized with an OPTIX 400S (3D Digital Corp, Sandy Hook, Conn) 3D laser scanner. The resolution of the scanner is 60 μm. The corresponding 3D digital models were reconstructed by using RapidForm® (INUS Technology Inc., Seoul, South Korea). The digital models were used to calculate the overall canine displacement in treatment.

For each canine, the origin of the coordinate system was set at the crown center on the pre-treatment model. The positive x-axis was directed buccally, y-axis distally, and z-axis apically for the left side canine; and the positive y-axis is directed mesially, for the right side.[26] To be consistent, the displacement components on the right side were converted to be expressed on the left side. The x and y axes formed a plane that was parallel to the posterior occlusal plane. [26]

The two digital models were superimposed by overlapping the 3D palatal (rugae) area. After the superimposition, the post-treatment model was in a comparable position with the pre-treatment model. Next, the crowns of the canine in the two locations were aligned using the entire crown surface points. Then the canine movement's six components in terms of translation along and rotation about the three coordinate axes were computed from the entries of the transformation matrix between the two crowns. The details of the superimposition and calculation methods were reported in a previous publication.[26]

Two of the displacements were used to calculate the movement rate, the resultant displacement and the displacement in the distal direction, y. The resultant displacements represent the total movement rate on the occlusal plane (XY plane); while the mesial-distal direction data were used to show the movement rate of the desired major movement in a space closure case. The rate of tooth movement considered in this study was determined by dividing total actual canine movement except the movement in the last TI by the treatment time in days (also excluding the days of the last TI). The resultant movement rate on

occlusal plane (XY plane), RG, was defined in Eq.1, where x, and y are the two translation components and T is the treatment time. The corresponding movement direction, θ, was defined in Eq. 2. It is the angle between the resultant movement direction on occlusal plane (XY plane) and the distal direction (Figure 1).

$$RG = \frac{\sqrt{x^2 + y^2}}{T}$$

Eq. 1

$$\theta = \tan^{-1}\left(\frac{x}{|y|}\right)$$

Eq. 2

To find the movement rate in the desired distal direction, the y component was used. The movement rate, RC, was defined in Eq. 3, which was directed distally.

$$RC = \frac{|y|}{T}$$

Eq. 3

The intrusion (+) and extrusion (−) were represented by the z-components in the coordinate system.

The means and standard deviations of the resultant movement rates, the movement direction angle, and movement rates in the distal direction were calculated. Differences in canine movement rates between controlled tipping side and translation side were compared with paired t-tests, since there was only one observation on each side for each subject. The equal-variance and normality assumptions were checked using normal probability plots. Differences were considered to be significant at $p < 0.05$.

The angle between the crown vestibular long axis of control tipping side canine and the occlusal plane (Figure 2) was measured using each patient's post-treatment CBCT image to ensure that the control tipping side canine was in its upright position when the treatment stopped.

Results

The resultant movement rates are shown in Figure 3. The rate for controlled tipping side canine ranged between 0.000 and 0.041 mm/day; and for translation side ranged between 0.001 and 042 mm/day. The movement rate difference varies among patients (between 0.000 and 0.029 mm/day).

Distal movement rates are shown in Figure 4. The rate for controlled tipping ranged between 0.000 and 0.040 mm/day; and for translation ranged between 0.000 and 0.035 mm/day. The movement rate difference varies among patients (between 0.000 and 0.026 mm/day).

The means and standard deviations of movement rates were shown in Table 1. Both on occlusal plane (XY plane) and in M-D direction, controlled tipping T-loops moved canines

33.3% (0.005/0.015) and 38.5% (0.005/0.013) faster than translation T-loops, respectively. In general, differences were statistically significant.

In both the occlusal plane (XY plane) data and the distal direction data, most patients had larger movement rate on their tipping side than the rate on their translation side. The differences were calculated by using Eq. 4.

$$Difference = Tipping\ Side\ Rate - Translation\ Side\ Rate \qquad \text{Eq. 4}$$

Six patients, Patient 2, 3, 4, 7, 16, and 17 had larger translation movement rate on occlusal plane and also in the distal direction (Figure 5 and 6). There is one patient, Patient 19, who has the same tipping and translation movement rate on the occlusal plane (Figure 5); and one patient, Patient 9, who has the same tipping and translation movement rate in the distal direction (Figure 6). The average difference is 0.005 mm/day on the occlusal plane and also in the distal direction.

The resultant movement directions on the occlusal plane (XY plane) varied from $-60.3°$ to $58.7°$ with an average being $16.64° \pm 26.583°$. Positive moving direction angle implied that tooth moved in the buccal and distal direction; while negative angle implied that tooth moved in the lingual and distal direction. Four tipping side and five translation side canines had the magnitude of the angles greater than $45°$.

The means and standard deviations of intrusion and extrusion movement (z-axis) rates were shown in Table 2. Intrusions are positive, and extrusions are negative.

The average angle between the control tipping side canine's crown long axis and the occlusal plane was $93.611° \pm 1.158°$ among all 21 patients, which indicated that the control tipping side canines returned to their upright positions when the treatments completed.

Discussion

The tipping and translation here represented treatment intentions, which were implemented using different M/F, higher M/F for translation and lower M/F for tipping. They did not represent clinical displacement patterns due to the fact that the T-Loop's M/F was very sensitive to the inter-bracket distance change due to tooth movement so that it changed as the tooth moves.[24]

This study measures the absolute displacement relative to the established coordinate systems. Using absolute displacement provides a more accurate description of the tooth movement in response to an orthodontic force than using relative displacement. Previous studies quantified relative displacement between two landmarks on the moving and anchorage teeth, respectively. Anchorage loss occurred clinically, which affected the measurement accuracy. Furthermore, the displacement was commonly described on a point. Choosing different points resulted in different displacement especially when a large tipping was involved. These factors would affect accuracy and make comparisons unreliable.

Reported maxillary canine retraction rates varied greatly. For the frictionless mechanics, the largest value reported was more than 2.5 mm/month among ten patients by using a calibrated sectional archwire,[27] while the smallest one was about 0.6 mm/month measured from six patients using a vertical loop, which would cause the force to rapidly decline.[28] The average value was about 1.6 mm/month.[18, 22, 29–31] In this study, the average movement rate on the occlusal plane calculated to 0.56 mm/month for the tipping side and 0.42 mm/month for the translation side (28 days per month). The values were relatively smaller compared to previous studies, likely due to different displacement quantification methods. The absolute 3D displacement of the crown center was calculated and only the movements in the occlusal plane were used (Eq. 1 and 3) in this study while others did point-to-point measurements, which might not be in the occlusal plane and in the directions clearly defined in this study, and might likely use relative displacement.

Intuitively, the same orthodontic load system would produce consistent clinical tooth movement rate. The phenomenon was not observed in this study, meaning that load system is not the only dominant factor controlling the tooth movement rate. The movement rate varied significantly among patients, which might be caused by multiple factors, such as bone quality, functional habit, and genotype.

Description of tooth movement with respect to a static reference helps clinician to quantify real tooth displacement and effects of various treatment strategies. Many previous studies reported tooth movement relative to an anchorage tooth, which might move during the treatment. Thus, the absolute movement was not obtained. In this study, movements of the moving and anchorage teeth were described relative to the rugae area. They were decoupled so that they could be analyzed separately. Thus, the reported movement would be the true response to the applied orthodontic load for a specified tooth. Furthermore, the intrusion/extrusion was reliably quantified, which was not possible from the relative displacement. On the other hand, clinicians could still use distal displacement to evaluate clinical outcomes in the space closure case. For this reason, the distal displacement, y, was used to calculate the closing movement rate.

Our previous study showed that M/F could not uniquely determine the pattern of clinical tooth movement when segmental T-loop was used.[26] As canine moved during treatment, M/F changed which caused the change of canine movement pattern. However, the results in this study showed that initial M/F still had important impact on the efficiency of tooth movement in terms of movement rate. Based on the segmental T-loop design for each patient, the initial M/F for the controlled tipping side was lower than the initial M/F for the translation side.[24] The results of this study showed that the canine with lower initial M/F moved statistically faster on the occlusal plane and in the distal direction for 71.4% patients (Figure 4 and 5, Table 1).

There were discrepancies between movement rates in the distal and on the occlusal plane. The difference was due to the coupled movement in either lingual or buccal direction. In this canine retraction treatment, with well-controlled orthodontic load system, ideally canines should move in the distal direction to close the space, thus both movement rates should be close. In reality, teeth had significant movements along other directions, i.e. buccal-lingual

(B-L) or occlusal-gingival (O-G) direction. The variation of the movement directions was large, indicating the well-controlled orthodontic load was not the only dominant factor controlling the tooth movement direction. The large variation in angle, indicated large inter-patient variation in the movement direction. There were also coupled movements in the O-G direction. The average movement rate was 0.004mm, which was very slow comparing with the movement rate in the occlusal plane (20%) or distal direction. This observation showed that no trend on intrusion or extrusion could be found.

Conclusion

1. Moment-to-force ratio (M/F) impacts on the canine movement rate in a maxillary canine retraction treatment with segmented T-loop mechanism.

2. Within the neighborhood of the ratio for translation, lower M/F moves canine faster than higher M/F both on occlusal plane and in the M-D direction.

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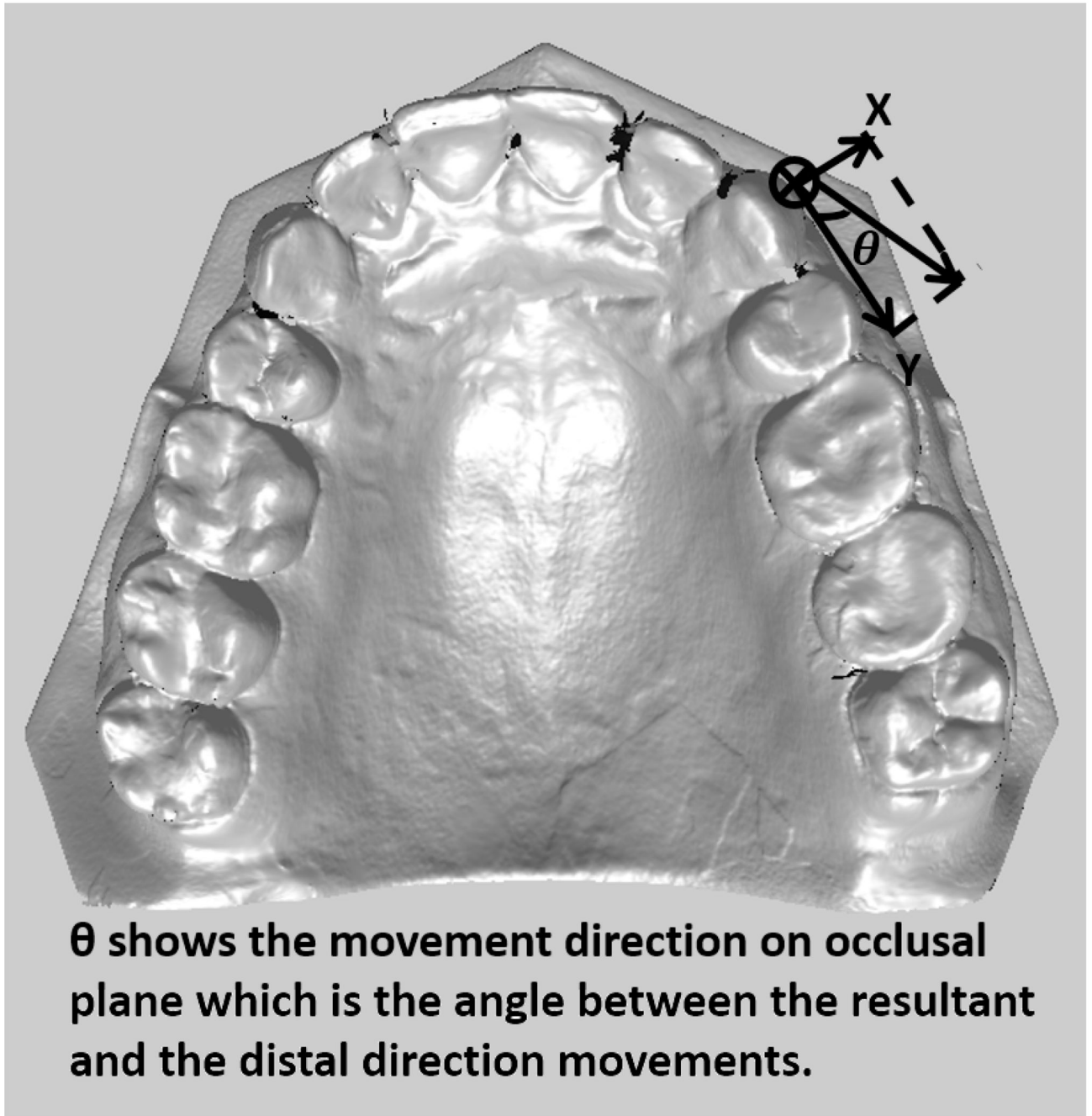
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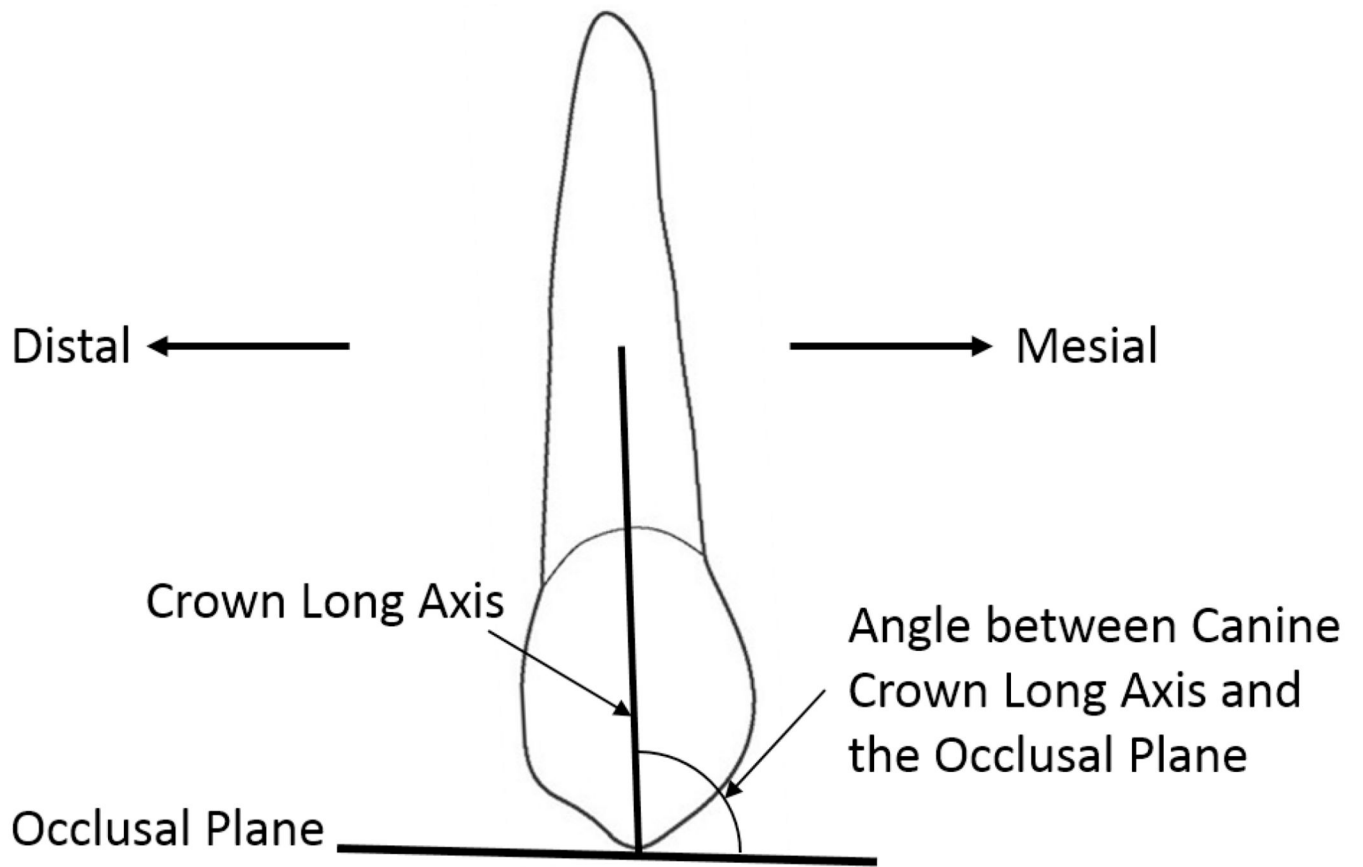**Highlights**

- The objective is to provide 3D clinical evaluation for canine movement rate.

- Both controlled tipping and translation strategies are studied.

- Movement rates quantified both on occlusal plane and in mesial-distal direction.

- Results show that moment-to-force ratios have impact on canine movement rates.

θ shows the movement direction on occlusal plane which is the angle between the resultant and the distal direction movements.

Figure 1.
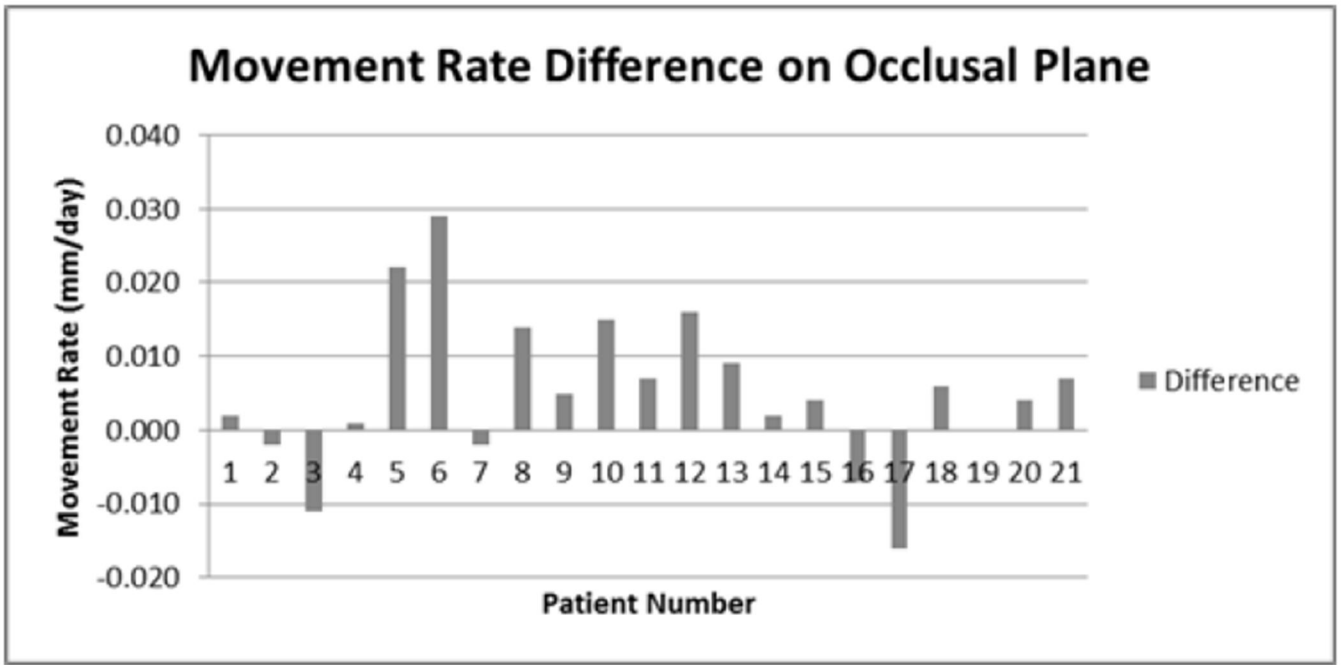Movement Directions on Occlusal Plane (XY Plane)

Figure 2.
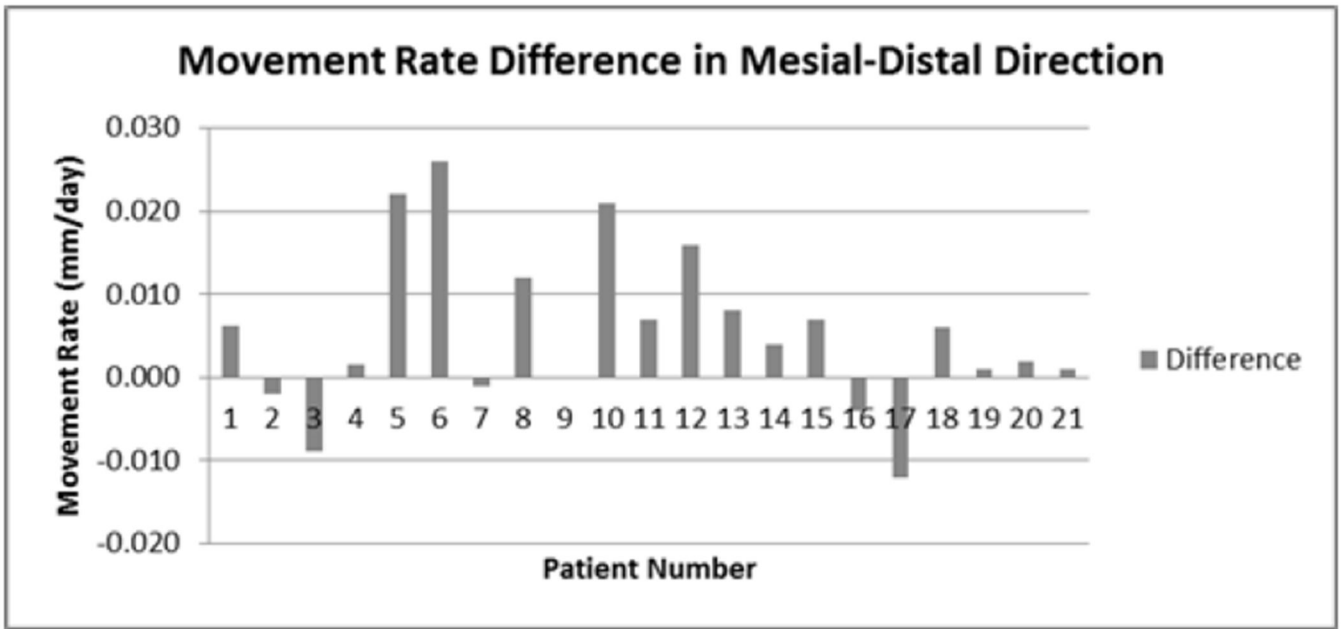Angle between Canine Long Axis and the Occlusal Plane
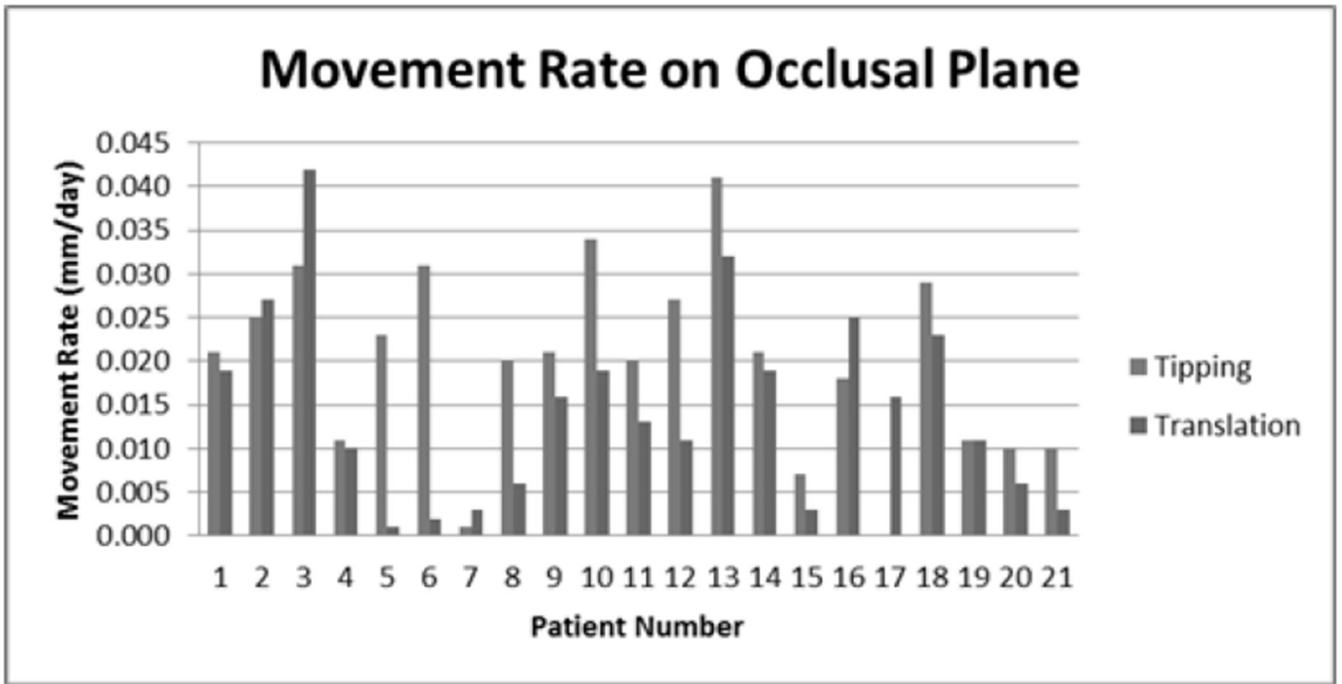
Figure 3.
Canine Movement Rate Results on Occlusal Plane (XY Plane)
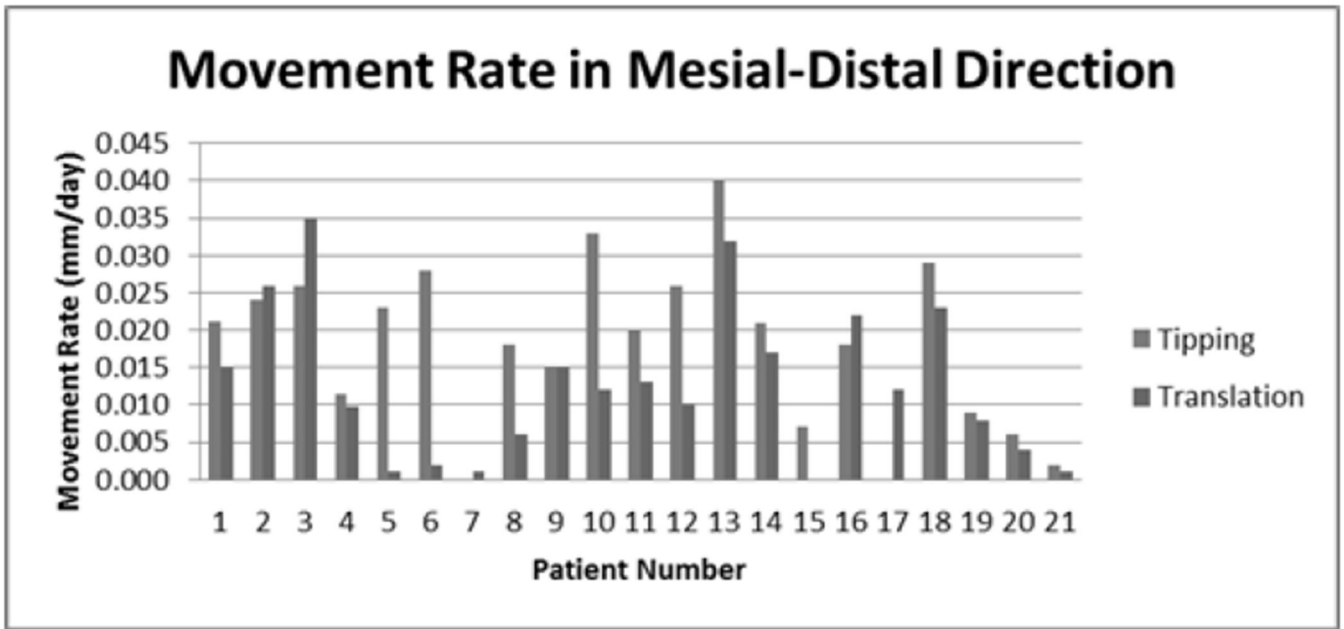
Figure 4.
Canine Movement Rate Results in Distal-mesial Direction

Figure 5.
Movement Rate Difference (Tipping Side Rate - Translation Side Rate) on Occlusal Plane
(XY Plane)

Figure 6.
Movement Rate Difference (Tipping Side Rate - Translation Side Rate) in Distal-mesial
Direction

Table 1

Movement Rates Statistical Analysis Results (mm/day)

Distance (mm)	Tipping	Translation	Difference	p-value
	Mean ± SD	Mean ± SD	Mean ± SD	
Occlusal Plane	0.020 ± 0.011	0.015 ± 0.011	0.005 ± 0.010	0.041
Mesial-Distal	0.018 ± 0.011	0.013 ± 0.010	0.005 ± 0.010	0.020

Table 2

Movement rate of Intrusion or Extrusion (mm)

Tipping	Translation	Overall
Mean ± SD	**Mean ± SD**	**Mean ± SD**
−0.002 ± 0.013	−0.006 ± 0.016	−0.004 ± 0.014