Original Article

Estimating the location of the center of resistance of canines

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ABSTRACT

Objective: To develop a method to quickly estimate the location of center of resistance (CR) in mesial-distal (MD) and buccal-lingual (BL) directions from the tooth's image.

Materials and Methods: The maxillary cone-beam computed tomography (CBCT) scans of 18 patients were used. Finite element (FE) models of the canines and their surrounding tissues were built based on their CBCT scans to calculate the locations of CR. Root length, centroid of the contact surface (CCS), and centroid of projection of the contact surface (CPCS) were also obtained from the images. The CCS and CPCS locations were projected on the tooth's long axis, which were represented as percentages of the root length measured from the root's apex.

Results: Using the FE results as the standards, the errors of using CCS or CPCS to estimate CR were calculated. The average location of CR calculated using the FE method was 60.2% measured from the root's apex in the MD direction and 58.4% in the BL direction. The location of the CCS was 60.9%. The difference in CR was 0.7% in the MD direction and 2.5% in the BL direction. The location of CPCS was 60.2% in the MD direction and 59.1% in the BL direction, which resulted in a 0.1% and 0.8% difference with the reference CR, respectively. The average difference of CR in the MD and BL directions was small but statistically significant ($P < .05$).

Conclusion: The locations of the CR of a human canine in the MD and BL directions can be estimated by finding the CPCSs in those directions. (*Angle Orthod.* 2016;86:365–371.)

KEY WORDS: Center of resistance; Canine

INTRODUCTION

Orthodontics requires controlled tooth movement. Tooth movement is three-dimensional (3D) and consists of both translation and rotation. The center of resistance (CR) has been used as an important reference point for controlling tooth displacement patterns, translation, or tipping. The concept of CR in tooth movement is equivalent to the concept of the mass center of a free body.[1,2] It is a conceptual point at which to apply a pure force to translate or a pure moment to rotate the tooth about it initially.[3]

Previous studies have reported that the location of the CR is approximately 1/2 to 2/3 of the root length measured from the root's apex, which was described on the tooth's long axis.[4–9] The range of results was large, and the results were primarily from animal studies or studies of individual patients. Recent studies also reported that the location of the CR depends on the direction of movement.[2,10,11] The CRs in the mesial-distal (MD) and buccal-lingual (BL) directions do not intersect in three dimensions, which means there is no 3D CR on the long axis of the tooth. Furthermore, the variation of the CR corresponding to different directions and within each direction needs to be quantified for better understanding of variations among the clinical treatment outcomes.

The finite element (FE) method was commonly used to analyze the locations of CR in previous studies[2,12–16] because of its unique ability to deal with completed biostructures in the clinic.[17–19] However, the FE method requires special training and is time consuming, which makes it impractical for use in the clinic. Alternative methods are needed.

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Individualized medical treatment requires patient-specific information. For better treatment planning and clinical research, a quick assessment method is needed to determine the patient-specific CR. Geiger and Lapatki[20] tested whether the centroid of root projection in the BL direction is close to the CR calculated using FE method on three human incisors. However, the conclusion was uncertain because of the small sample size, which did not show the variation and did not fully support the use of the method in a clinic. Furthermore, the method has not been used to determine CR in the MD direction. Further investigation is needed to assess the method.

The location of the CR depends on the geometry and boundary condition of the root and its supports from the periodontal ligament (PDL) and bone. A method that assumed PDL functions as a two-dimensional projection in a certain direction was proposed.[9] However, tooth displacement depends on the 3D contact surface area between the root and PDL. Thus, the location of the CR might be a function of the contact surface. Based on the mass center concept, we hypothesized that the centroid of the contact surface (CCS) between root and PDL can be used as the location of CR. To ease the computation, we further hypothesized that the CR can be estimated based on the centroid of projection of the contact surface (CPCS) in the corresponding direction.

The objectives of this study were to (1) determine whether CCS and CPCS can be used to find the locations of the patients' CRs corresponding to the MD and BL directions and (2) find the variations between the two directions and within each direction.

MATERIALS AND METHODS

The maxillary cone-beam computed tomography (CBCT) scans of 18 patients (7 male and 11 female patients) were used in this study. The inclusion criteria included the requirements of typical radiographically identified dental anatomy (average root sizes, bone insertion, and shape) and healthy periodontal tissues with generalized probing depths <3 mm and no radiographic evidence of periodontal bone loss. The research protocol was approved by the Institutional Review Board and consented to by the patients. The average age of patients was 19 ± 9 years, and ages ranged from 12 to 47 years. The CBCT scans were performed on an i-CAT Imaging System (Imaging Sciences, International, LLC, Hatfield, Penn). The voxel size was 0.25 mm and the scan time was 26.9 seconds.

For each patient, the left or right maxillary canine was randomly selected for calculating and comparing CR. The root length was measured from the root's apex to the average height of alveolar crest using MIMICS 13.0 (Materialise, Leuven, Belgium).

CBCT images were imported into MIMICS to construct the 3D root and alveolar bone. The root and surrounding alveolar bone were segmented. The contour lines were exported to Pro-Engineer (Parametric Technology Needham, MS) to rebuild the geometries, and then the solid parts were exported to ANSYS 14.5 (ANSYS, Inc, Canonsburg, Penn.) to build the finite element model.

The FE model includes root, fiber-reinforced PDL with 0.2-mm thickness, and alveolar bone. The geometry of a canine was obtained from each patient's CBCT images. The thickness of human PDL was reported to be around 0.1 to 0.3 mm (average $=$ 0.2 mm).[21,22] Due to a lower CBCT resolution (0.25-mm voxel size), the PDL layer was not clearly shown in the images. Thus, the root was identified first (see Figure 1a). The PDL and cortical bone were grown from the surface of the root. The thickness of the PDL and cortical bone was 0.2 mm each.[19] The PDL was modeled as fiber-reinforced matrix. Two-node link elements were created to connect the nodes on the root and cortical bone surfaces to simulate the fibers.[11] A 10-node tetrahedral element was used to model the bone and tooth (see Figure 1b). Details of modeling were reported previously.[11] To calculate the location of CR using the FE method, a pure moment was applied to the crown in the MD and BL directions, respectively (see Figures 1c,d). The center of rotation was determined, which was considered to be the CR. Theoretically, the location is independent on the site where the pure moment is applied, which was confirmed in our pilot study. Applying the moment at different locations minimally affected CR locations ($<$0.4%).

The CCS was calculated. As shown in Figure 2, the outer layer of the root was formed by eroding the root outer surface with one voxel. The outer surface was considered the contact surface. The voxel on the surface and its coordinates (x, y, and z) were used to compute the location of CCS of the contact surface using formula 1.

The CPCS was also computed. As shown in Figure 3, the root surface voxels were projected to the MD and BL planes, respectively. The projection was made using MIMICS. The CPCSs in the corresponding directions were computed using formulas 2 and 3.

$$CCS(x,y,z)=\frac{\sum voxel(x,y,z)}{number\ of\ voxels} \quad (1)$$

$$CP_{MD}(y,z)=\frac{\sum voxel(y,z)}{number\ of\ voxels} \quad (2)$$

$$CP_{BL}(x,z)=\frac{\sum voxel(x,z)}{number\ of\ voxels} \quad (3)$$

The results were compared with those obtained from the FE analysis for validation. A paired *t*-test was

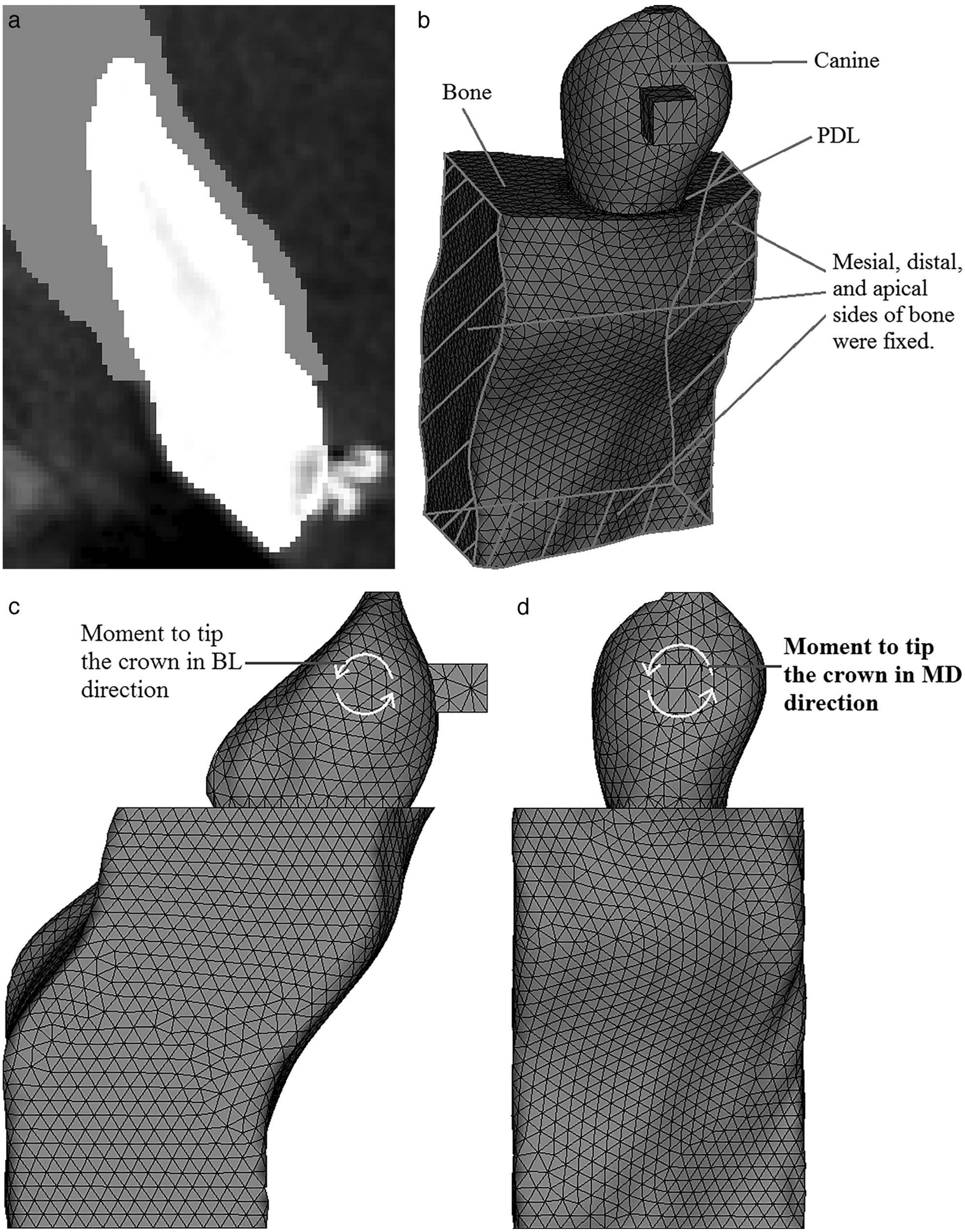

Figure 1. Creation of the finite element models. (a) Segmentation of the root and bone. (b) Meshes and boundary conditions. (c) Loading condition in the BL direction. (d) Loading condition in the MD direction.

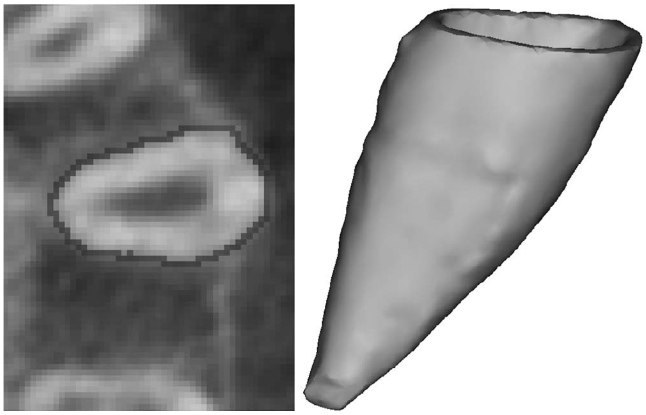

Figure 2. Segmentation of the root and creation of the root's surface layer for making the projections required to calculate the centroids.

applied to identify the difference of CR in the MD and BL directions with 95% confidence intervals.

RESULTS

The root length, locations of CR in the MD and BL directions, and difference between the calculated CRs in both directions using the FE method are shown in Table 1. The average root length was 16.5 ± 1.7 mm. The average location of the CR was 60.2% ± 2.6% measured from the root's apex in the MD direction and 58.4% ± 3.2% measured in the BL direction. The average difference between the CRs in the two directions was 1.8% ± 2.8%. The difference was statistically significant ($P = .012$) from the paired *t*-test. The FE analysis results were used as the reference locations of CR.

The locations of CCS and its difference from the CRs calculated using the FE analysis in both MD and BL directions are shown in Table 2. The location of CCS was 60.9% ± 2.6% measured from the root's apex. The difference in the reference CR was 0.7% ± 1.0% occlusally in the MD direction and 2.5% ± 2.4% occlusally in the BL direction. The variation of difference of the CR in the BL direction was larger. The largest variation was 7.4% in the BL direction, compared with 2.9% in the MD direction.

The locations of CPCS in the MD and BL directions and their differences from the reference CRs in the corresponding directions are shown in Table 3. The location of CPCS in the MD direction was 60.2% ± 2.3%, which resulted in a 0.1% ± 0.8% difference apically from the reference CR. The location of CPCS in the BL direction was 59.1% ± 1.7%, which resulted in a 0.8% ± 2.4% difference occlusally from the reference CR. The CPCS was closer to the reference CR in the MD direction than in the BL direction. However, the variation was similar to that found using the CCS method.

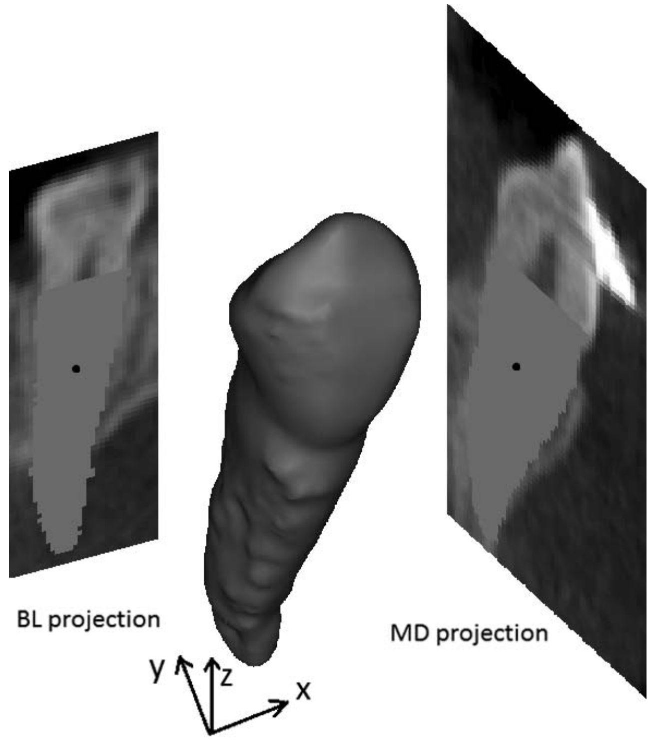

Figure 3. Projections of the root contact surface in the MD and BL directions and determination of the location of the CPCSs in these directions.

DISCUSSION

The idea of using CCS or CPCS to estimate the location of CR came from the concept of mass center. In dynamics, if a force is applied to the mass center of a free body, the body translates. Although a tooth is not a free body, its displacement depends on the contact surface, which is 3D. The centroid is where the resultant force acts; thus, it may cause translational displacement. This study confirmed the hypothesis.

The locations of the CRs in the MD and BL directions were statistically different from each other, although the average difference was small (0.3 mm). If this amount is considered insignificant clinically, the location of CR calculated in one direction may be used for the other direction. However, clinicians may keep in mind that the difference may be large for some patients, like patients 3 and 4 in this study, because of the shape of the root (see Table 1).

Our study has narrowed the location of the CR in MD direction down to 60.2% ± 2.6% from the root's apex. The variation (52.1% to 64.9%) also provides a useful reference for clinical treatment. Compared with previous studies, the result of our study was close to that of previous studies on single root teeth (60%,[3] 60%,[6] 63% to 65.6%,[7] 57.2%,[20] and 61.7%[11]).

The average CR in the BL direction was located more occlusally than in some previous studies

Table 1. Root Length Measured Using MIMICS and CRs Calculated Using the FE Method (Measured from the Root's Apex)[a]

Patient No.	Root Length (mm)	FE_MD	FE_BL	Difference: FE_BL Minus FE_MD
1	19.5	56.9%	57.5%	0.6%
2	15.6	60.0%	56.4%	–3.6%
3	17.2	64.9%	56.9%	–8.0%
4	16.3	61.0%	54.3%	–6.7%
5	18.1	60.3%	62.7%	2.4%
6	18.8	61.7%	64.1%	2.3%
7	14.1	59.6%	58.8%	–0.8%
8	15.9	61.4%	60.0%	–1.4%
9	15.4	61.4%	59.3%	–2.1%
10	18	58.5%	60.9%	2.4%
11	15.8	52.1%	49.6%	–2.5%
12	13.5	61.6%	60.8%	–0.8%
13	19.1	61.1%	59.2%	–1.9%
14	15.4	60.7%	56.6%	–4.1%
15	15.7	59.7%	58.4%	–1.2%
16	15.8	61.7%	58.3%	–3.4%
17	17.9	62.2%	59.3%	–2.9%
18	15.3	59.1%	57.1%	–2.0%
Average	16.5	60.2%	58.4%	–1.8%
SD	1.7	2.6%	3.2%	2.8%

[a] CR indicates center of resistance; FE, finite element; MD, mesial-distal; BL, buccal-lingual; SD, standard deviation.

Table 2. Calculated CCSs and Their Difference From the reference CRs in the MD and BL Directions (Measured From the Root's Apex)[a]

Patient No.	CCS	Difference: CCS Minus FE_MD	Difference: CCS Minus FE_BL
1	56.9%	0.0%	–0.6%
2	61.4%	1.4%	5.0%
3	64.3%	–0.6%	7.4%
4	60.3%	–0.7%	6.0%
5	61.5%	1.2%	–1.2%
6	62.3%	0.6%	–1.7%
7	61.2%	1.6%	2.4%
8	62.7%	1.4%	2.7%
9	61.4%	0.0%	2.1%
10	61.5%	2.9%	0.6%
11	52.1%	0.0%	2.5%
12	62.4%	0.8%	1.6%
13	61.1%	0.0%	1.9%
14	61.4%	0.7%	4.7%
15	61.0%	1.4%	2.6%
16	61.7%	0.0%	3.4%
17	61.8%	–0.5%	2.5%
18	60.7%	1.6%	3.6%
Average	60.9%	0.7%	2.5%
SD	2.6%	1.0%	2.4%

[a] CCS indicates centroid of the contact surface; CR, center of resistance; MD, mesial-distal; BL, buccal-lingual; FE, finite element; SD, standard deviation.

(43.5%[20] and 53.8%[11]), close to the finding in one study (58%[23]), and lower than the finding in another (66%[5]). The potential explanations of the difference could be attributed to the sample size, reference point, and tooth difference. Our study had a sample size of 18, which was much larger than in previous studies. Our study used the average height of the alveolar crest as the reference, whereas other studies used the highest point of the alveolar crest.[5,20] Furthermore, some of the results were from incisors, which may contribute to the discrepancy.

Our study has shown that the locations of the CR can be estimated using the CCS of the root. The CCS is a point in the space that is not necessarily on the long axis of the tooth. However, only its projection on the long axis is of interest. The difference between the CCS and the reference CR in the MD direction was small (0.7% ± 1.0% or 0.12 ± 0.17 mm). The difference between the CR in the BL direction was larger (2.5% ± 2.4% or 0.41 ± 0.40 mm). The average CCSs were located occlusally with respect to the reference CRs in both directions, which would result in a smaller moment-to-force ratio for translation.

The CPCS method showed better estimates of CR than the CCS method. The difference in the reference CR (0.1% ± 0.8% or 0.02 ± 0.13 mm apically in MD direction; 0.8% ± 2.4% or 0.13 ± 0.40 mm occlusally in BL direction) was smaller than the findings with the CCS method. Therefore, using CPCS method will give a better estimate than the CCS method.

Our study showed that the CR can be estimated using the CPCS method. This study had larger sample size (18 vs 3[20]), which allowed us to study the average CR locations and variations. The methods were validated by well-controlled FE analyses. Discrepancies existed with the previously published results. These may be due to the difference in reference point (average vs highest point of alveolar crest), modeling techniques, and tooth difference (canine vs incisor). The CR location would be affected if the definition of the tooth length was different. For our modeling, an effort was made to create reliable FE models. In this study, the same CBCT scanning setting was used for all the scans and for standardized imaging process without altering original images using any cosmetic processing. The FE model was composed of crown, root, PDL, cortical bone, and cancellous bone. The PDL was modeled as fiber-reinforced structure. These measures increased the accuracy of the FE results and the validity of the CPCS method.[20]

The CR concept has been widely used to develop treatment strategy. This study demonstrated interpersonal variations. Some patients have an abnormal CR location, such as patient 11. It will be beneficial to have a method that can quickly estimate the CR location so that individualized treatment can be delivered. CBCT or x-ray radiography are commonly used in the clinic. Root surface or its projections can be easily obtained.

Table 3. Calculated CPCSs in the MD and BL Directions and Their Difference From the Reference CRs in the Corresponding Directions (Measured From the Root's Apex)[a]

Patient No.	CPCS_MD	Difference: CPCS_MD Minus FE_MD	CPCS_BL	Difference: CPCS_BL Minus FE_BL
1	57.5%	0.6%	55.7%	–1.8%
2	60.7%	0.7%	60.0%	3.6%
3	63.7%	–1.2%	60.6%	3.7%
4	60.3%	–0.7%	57.0%	2.7%
5	59.7%	–0.6%	60.3%	–2.4%
6	61.2%	–0.6%	61.2%	–2.9%
7	60.4%	0.8%	58.0%	–0.8%
8	61.4%	0.0%	60.7%	0.7%
9	60.7%	–0.7%	60.0%	0.7%
10	59.7%	1.2%	59.1%	–1.8%
11	52.1%	0.0%	56.3%	6.7%
12	60.8%	–0.8%	61.6%	0.8%
13	60.5%	–0.5%	59.7%	0.5%
14	60.7%	0.0%	58.2%	1.6%
15	60.3%	0.7%	60.1%	1.7%
16	61.0%	–0.7%	58.8%	0.5%
17	61.7%	–0.5%	58.5%	–0.8%
18	60.3%	1.2%	58.1%	1.0%
Average	60.2%	–0.1%	59.1%	0.8%
SD	2.3%	0.8%	1.7%	2.4%

[a] CPCS indicates centroid projection of the contact surface; CR, center of resistance; MD, mesial-distal; BL, buccal-lingual; FE, finite element; SD, standard deviation.

Then, the CR location can be estimated quickly, which will benefit clinicians and patients.

This study provides a foundation for a simple and reliable method to predict the locations of the CR in the MD and BL directions clinically. In this study, the root length was measured in three dimensions. The projections were on the planes perpendicular to the occlusal plane, and the location of CPCS was represented using the percentage of root length. The projection of the root and the centroid could be easily found from the CBCT images. To be consistent, the occlusal plane was used as the reference plane. It is also possible to apply the method to conventional radiographic images, which are more commonly used in clinics. The projection of the root in the BL direction is available from the radiographic images. However, the feasibility needs to be further investigated for the following reason: the root length measured on a radiographic image may not be the true length in three dimensions. Tilting the tooth affects the root length and distorts the projected images, which may affect the results. The CPCS in the MD direction from the radiographic image is not available, but the CR location may be estimated based on the ratio between the two CRs obtained from this study.

Although the FE method is more convenient and reliable to identify the complex movement nature of orthodontic treatment, it is still not practical to apply the method to every individual patient. Then CPCS method may be used to compute CR while FE method is not applicable. It only requires the CT scan and basic image processing. It also has the potential to estimate CR from radiographic images.

CONCLUSION

- The locations of the CRs in the MD and BL directions are small but statistically different.
- The locations of the CRs of a human canine in the MD and BL directions can be estimated by finding the CPCSs in the two directions.

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