A Multi-Directional Analysis of the Center of Resistance using Finite Element Model of the Human Mandibular Canine

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Abstract

Background

The most important factor determining the quality of orthodontic tooth movement is the relationship between the force and the tooth center of resistance. Tooth supporting structures features affect the center of resistance location and these features varies in different areas around the specific tooth. So the aim of this study is the multi-planar analysis of the center of resistance using finite element models of the human mandibular canine to find the exact location of the center of resistance when viewed from different aspects.

Method

The left mandibular canine, periodontal ligament, cortical bone and spongy bone designed in Soidwork (version 2021) according to a contralateral canine with a complete eruption in a case with an impacted canine which has been ordered for CBCT. the tooth dimension was slightly modified according to wheelers dental anatomy. The meshed model was created. A 1N.mm couple was applied to the model and the center of resistance was evaluated from different 24 planes with 15 degrees intervals.

Results

The location of human mandibular center of resistance is different in horizontal plane when evaluated in different directions. It is in the range of 46–86% of canine root length from the apex and moves up to 4.48 millimeters occlusogingivally. In the buccal or lingual directions CRes location was found more apical than its mesial or distal counterparts.

Conclusions

the location of the CRes changes when evaluated in different directions related to supporting tissue features. It can therefore be concluded that canine requires a higher M/F for buccolingual translation than for a mesiodistal translation

Introduction

Controlled tooth movement is one of the basic principles of orthodontic treatment. Tooth movement is assessed in a three-dimensional space. It consists of translation, tipping, extrusion, intrusion and rotation. (1) In order to evaluate the patterns of tooth displacement, the center of resistance (CRes) has been considered as a crucial reference point. CRes in a restrained body is an equivalent for the concept of center of mass in free body(2).
Tooth movement is described by certain force and moment in 2-dimensional (2D) planes, Clinically. The location of the tooth's CRes determines each required displacement. The anatomy and physical properties of the root and supporting structures have resulted in this location(3).

Different factors affect the exact CRes location, including root length and surrounding osseous level. A greater effect is caused by root length than by bone height(4). The canine's CRes has been estimated at 45% of its root length, but the CRes may be located at 35% of this length when evaluating a smaller tooth (5). Due to reduced root length and altered root shape caused by root resorption, CRes is displaced coronally(5–7).

According to Yoshida et al., the upper central incisor's CRes is primarily dependent on the palatal osseous plate level and only secondarily on the labial plate level when palatal forces are applied(8). As Geramy (2000) reveals, alveolar bone loss is correlated with an increase in the moment/force ratio (M/F) needed to produce translation of tooth. Center of resistance shifts toward the apex with bone loss, although its relative distance from the alveolar crest also decreases(9).

As investigated by previous researches, the CRes can be found between half and two thirds of the root's length, measured from the apex of the root(3, 8, 10–12). Moreover, according to recent studies, the movement's direction affects where the CRes are located(7, 13). To be more specific, it is suggested to propose a volume of CRes since the asymmetric geometries may prevent the CRes from existing as a single point in three dimensional space(2). In order to understand the variability in clinical treatment results, it is also necessary to quantify the difference in the CRes relating to various directions and in each direction.

Any such movement can also be determined by its related center of rotation (CRot), which is described as the point on the long axis or its extension that remains stationary as the rotational component of the tooth movement occurs(14, 15). Usually, there are moments that influence the tooth movement because forces implemented by the orthodontist typically do not pass through the CRes.

The CRes and CRot can be located in many different ways. Applying a couple in various directions is a feasible option for determining the tooth CRes. A couple is defined as two forces of equal magnitude with parallel lines of action but in opposite directions that are not collinear(16). As a result, using a couple produces a pure rotation in the tooth where the CRot and CRes are located in the same area.

Determining the distance between the tooth' center of rotation and the center of resistance is the one of most used technique for describing the type of tooth displacement. The effect of controlled moment to force ratio, on the pattern of tooth movement in one plane has been assessed by previous researchers(17). One study concentrated on obtaining a formula by exerting a force perpendicular to a canine's long axis, which has a parabolic root shape. It is known as the Buestone formula (M/F = 0.068*h^2/D), where h refers to the distance from the alveolar crest to the apex and D refers to the distance between the CRes. and the CRot(18).
Geramy et al. investigated the accuracy of Nägerl Theory of proportionality which indicate that by applying a single force closer to the cervical region of the tooth, location of the CRot shift toward apical area, and resulting less inclination change. They approved the applicability of this theory in an alveolar bone loss situation (19).

The force magnitude also can affect the type of tooth movement; More precisely, even with the same moment-to-force ratio, it may be changed by increasing the force. This is related to nonlinear nature of the periodontal ligament (PDL), which becomes significant beyond a specified strain threshold (20).

Analytical methods as well as experimental methods have been used to locate the CRes. For instance, strain gauges and laser-holographic techniques were implemented to the investigation of tooth movement. Electrical extensometers that are connected to the points of a structures to monitor their movement, are called strain gauges. Each extension leads to an increase in the resistance of strain gauge, which is measurable electronically. The limitation of this method is that even the smallest head motions can dramatically reduce the accuracy of tooth movement (7). Strain gauges could potentially damage periodontal ligament during insertion, according to McGuiness et al (21). A magnetic sensing system was used in order to locate that central incisor center of resistance were changed by osseous level (8). CRes location of the anterior segment of dental arch have been studied through a photo elastic model was used on Matsui et al study (22). However, most studies were reported CRes locations of specific teeth using simplified idealized finite element models (23, 24). CRes at the most apical and occlusal positions relate to triangular as well as rectangular root shapes, reported using a 2-dimensional mathematical model (3).

As reported by Christiansen and Burstone, a more apically located CRes in root-like shape was measured. Compared with the CRes location was reported by Yoshida et al. These findings suggested that the CRes in tapered root, is more occlusal (8, 25).

A useful computational technique for analyzing responses to actual physical variables, such as loads and biomechanical responses, that occur during medical and dental procedures is finite element (FE) method (26). Through the reconstruction of the appropriate geometry and discretization of the domain into a finite mesh, this method seeks numerical solution of partial differential equations with the least need to implement clinical trials on patients (27). Improved orthodontic tooth movement prediction in clinical practice is one of the main priorities of FE-based modeling of the tooth and its surrounding structures, as compared to clinical studies (28).

According to finite element models used by Tanne et al. and Vollmer et al., the CRes of upper central incisor and a canine were located at a distance that is equal to 24% and 42% of the root length, respectively (6, 10).

Later research by Tanne et al. determined that the maxillary central incisor CRes was 34% of root length (29). The size of the model around the tooth under analysis, the type of terminal conditions, and
the amount of mesh refinement required for accurate results all have an impact on the various results (30).

**Methods**

Ethics approval was granted by the Research Ethics Committee of school of Dentistry - Tehran University of Medical Sciences (approval ID: IR.TUMS.DENTISTRY.REC.1401.129)

The left mandibular canine with 0.018 x 0.030 inches edgewise bracket without internal prescription, on the facial axis point (FA) of crown was designed using Solidworks software (version 2021). The bracket was connected directly to the buccal surface of tooth crown. (Fig. 1)

A contralateral canine with a complete eruption in a case with an impacted canine which has been ordered for CBCT was selected for modeling. The data needed to model the surrounding tissues was gathered from CBCT and the tooth dimension was slightly modified according to wheelers dental anatomy (31).

In this study, the tooth, alveolar bone, and periodontal ligament were assumed to be isotropic, homogeneous, linear elastic materials. Physical properties of different materials were assigned according to studies of Geramy. (Table 1) Then the designed model was meshed. (Fig. 2)

For the boundary conditions, model bases were fixed. The contacts between materials (PDL and tooth, PDL and cancellous bone, PDL and cortical bone, cancellous bone and cortical bone, tooth and bracket) are all bonded.

A 1 N.mm couple was applied at each stage of the analysis (at the designed bracket on the tooth). In the first stage the couple was applied in bracket when viewed buccally (= 0-degree stage). The 360 degrees around tooth crown (when viewed occlusally) was divided to 24 equal sections, which each plane is considered at an angle of 15 degrees to the adjacent plane The couple was applied in each plane. To calculate the exact location of the CRes, a path of nodes was defined between the cusp tip and apex containing 49 nodes. According to basic mechanics, a couple produces a displacement in tooth with a CRot which is coincide with the CRes. considering the inability of a couple to displace the CRes. All displacements along the defined path was recorded. (24 stages of analysis  49 nodes along the path = 1176 dots) a python coding was conducted to find the exact location of CRot in different stage of couple application.
Table 1  
Mechanical properties of each material(32).

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's modulus (MPa)</th>
<th>Poisson's ratio</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth</td>
<td>20,300</td>
<td>0.26</td>
<td>Geramy et al., 2016</td>
</tr>
<tr>
<td>PDL</td>
<td>0.667</td>
<td>0.49</td>
<td>Geramy et al., 2016</td>
</tr>
<tr>
<td>Spongy bone</td>
<td>13,400</td>
<td>0.38</td>
<td>Geramy et al., 2016</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>34,000</td>
<td>0.26</td>
<td>Geramy et al., 2016</td>
</tr>
<tr>
<td>Stainless steel bracket</td>
<td>200,000</td>
<td>0.26</td>
<td>Geramy et al., 2016</td>
</tr>
</tbody>
</table>

Results

The results of the finite element analysis showed that the location of the center of resistance of the mandibular canine is in the range of 46–86% of the root length from apex. (Fig. 3) In addition, it was shown that the location of the center of resistance moves inciso-apically when evaluated in 24 different planes which each plane is considered at an angle of 15 degrees to the adjacent plane, up to 4.48 mm. The location of the center of resistance in planes related to mesial surface (60 degrees to 120 degrees) as well as distal surface (240 degrees to 300 degrees) was more incisal than planes related to buccal surface (0 degrees to 45 degrees and 315 degrees to 360 degrees) and lingual surface (135 degrees to 225 degrees). (Fig. 4) and (Table 2)
Table 2
Inciso-apical location of CRes in twenty-four different planes

<table>
<thead>
<tr>
<th>Orientation(degree)</th>
<th>CRes(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.8382</td>
</tr>
<tr>
<td>15</td>
<td>7.7108</td>
</tr>
<tr>
<td>30</td>
<td>7.4714</td>
</tr>
<tr>
<td>45</td>
<td>6.5429</td>
</tr>
<tr>
<td>60</td>
<td>10.4284</td>
</tr>
<tr>
<td>75</td>
<td>8.6552</td>
</tr>
<tr>
<td>90</td>
<td>8.3428</td>
</tr>
<tr>
<td>105</td>
<td>8.204</td>
</tr>
<tr>
<td>120</td>
<td>8.1151</td>
</tr>
<tr>
<td>135</td>
<td>7.2198</td>
</tr>
<tr>
<td>150</td>
<td>7.0017</td>
</tr>
<tr>
<td>165</td>
<td>6.7887</td>
</tr>
<tr>
<td>180</td>
<td>6.5351</td>
</tr>
<tr>
<td>195</td>
<td>6.1309</td>
</tr>
<tr>
<td>210</td>
<td>5.5357</td>
</tr>
<tr>
<td>225</td>
<td>6.5429</td>
</tr>
<tr>
<td>240</td>
<td>10.4284</td>
</tr>
<tr>
<td>255</td>
<td>9.438</td>
</tr>
<tr>
<td>270</td>
<td>8.3213</td>
</tr>
<tr>
<td>285</td>
<td>8.2037</td>
</tr>
<tr>
<td>300</td>
<td>8.1158</td>
</tr>
<tr>
<td>315</td>
<td>8.0457</td>
</tr>
<tr>
<td>330</td>
<td>7.8182</td>
</tr>
<tr>
<td>345</td>
<td>7.9141</td>
</tr>
<tr>
<td>360</td>
<td>7.8324</td>
</tr>
</tbody>
</table>
Recognition of the exact location of the CRes has become more essential to guaranteeing predictable orthodontic tooth movement during treatment(22).

Center of resistance has been described as a point when located with a single force result in tooth translation in the direction of the force's line of action (33).

According to Burstone and Pryputniewicz, the CRes of the tooth was located one-third of the distance from the alveolar crest to the apex(12). the aim of the current study was to more precisely locate the center of resistance by detecting it from different planes, to make efficient its application in orthodontic tooth movement.

Using finite element method, Reimann et al. describe the CRes as a range rather than a single point; they claim that due to the influence of factors such as the play between the wire and the bracket and the wire deformation, the size of the orthodontic wire was reported to alter the center of resistance. Because of that, no play between the wire and the bracket was anticipated in the Reimanns study, which provided the wire the material qualities of the rigid body(34).

One of the most important factors affecting the position of CRes is root shape. The maxillary anterior teeth have conical roots and by moving from the cervical region to the apical region, their tapering becomes larger. On the other hand, the tapering degree of the roots of mandibular anterior teeth is weak because their roots are cylindrical. In the maxillary premolar teeth, the trunk region is divided into the palatal and buccal roots, however. In the mandibular premolar teeth, usually one root is present. There are three and two roots in the maxillary molar and the mandibular molar respectively. The mandibular teeth's center of resistance is typically found more apically than maxillary teeth duo to the cervical region of the upper roots is more developed(35).

The results of the finite element analysis showed that, the center of resistance position of the mandibular canine tooth in 24 different planes with 15 degrees intervals, moves up to 4.48 mm occlusogingivally. That is, the position of CRes estimated in one direction could not be used in the other direction if this amount (4.48mm) was considered clinically significant.

The location of CRes for buccal (0 degree = 7.83mm ) or lingual(180 degrees = 6.53mm) directions is more apical than its mesial(90 degrees = 8.34mm)or distal counterparts(270 degrees = 8.34mm). It can therefore be concluded that canine requires a higher M/F for buccolingual(BL) translation than for mesiodistal(ML) one.

According to Brandon et al.'s investigation into the effect of orthodontic force direction on the CRes of dog teeth, the CRes are located more apically in buccolingual tooth movement than its mesiodistal counterpart(36).

In order to determine the positions of CRes, Jiang et al. created Finite element models of the canine teeth with their supporting structures using their CBCT scans. To estimate CRes, they used the images to determine the root length, centroid of the contact surface, as well as centroid of projection of the contact
surface. They reported a small difference between the location of CRes in the mesiodistal and buccolingual directions (0.3 mm) although this difference was statistically significant (37). This amount is considered insignificant clinically however in our study the amounts related to the location of CRes for different directions was up to 4.48 mm.

Some previous investigations located the average CRes in the buccolingual direction more occlusally than mesiodistal direction, inconsistent with the finding in one study (36–38). The upper canine teeth was chosen at random in order to estimate CRes, according to Jiang et al (37). In a study by Geiger et al., CRes locations of the upper right central incisor were assessed in both a 3D and 2D models (38). Meyer et al. investigated the positions of the CRes in the buccolingual and mesiodistal directions of the dog's mandibular central incisors (36). However, in this study, mandibular canine was modeled base on Wheeler's dental anatomy textbook (31).

The results of the finite element analysis showed that, the positions of the center of resistance of the mandibular canine tooth in different directions are in the range of 46–86% of canine root length if considered from the alveolar crest.

The results of this study are consistent with the majority of other reported CRes locations that is 34–64% of root length from the alveolar crest (3, 7, 8, 10–12, 29). The results of current study also demonstrate a wider range for CRes locations and a significant difference between them in the various directions.

A variety of factors, such as the root being wider in one direction than another, might cause the locations of CRes to differ in various directions. The findings demonstrate that displacement and tipping caused by force are reduced the wider the root. Less tipping necessitates smaller uprighting corrective moments, suggesting a more occlusal position for CRes. Furthermore, difference of CRes in the mesiodistal and buccolingual directions may be large for some patients, because of the root shape (3, 8, 11).

Differences between the findings in such studies can be due to the root cross-section shape, which is not symmetrical, as well as the form of alveolar bone in the crestal areas, which has different morphology in various areas around the tooth.

Another reason responsible for different locations of CRes in the various directions, is alveolar bone level difference in different teeth or different area of one tooth, as previous studies reveal, Alveolar bone loss is correlated with an increase in the moment/force ratio needed to induce translation. Center of resistance shifts apically with bone loss, although its relative distance from the alveolar crest also decreases (9).

As modeled in this study, alveolar bone level of intact mandibular canine in the mesiodistal direction is more occlusally than buccolingual direction. Therefore, it can be concluded that the locations of CRes moves toward apex in buccolingual areas, consistent with the results of this study.

It should be noted that two teeth may have equal relative CRes positions, however if their root lengths differ, the moment to force ratio needed for bodily movement will be different. Hence, if the relative location is used, details about tooth length is needed for clinical evaluation of the CRes (36).
Due to PDL anisotropy, which is brought on by the non-uniformly oriented fibers that only display resistance in tension along their individual lengths, the location of the CRes would shift nonlinearly (39). The isotropic, linear elastic matrix which is modeled, functions in both compression and tension. Orthodontic forces are small compared to functional loads, and the matrix's orthodontic strains and stresses would be expected to be linear.

In a finite element analysis of a maxillary first premolar, Roberto Savignano et al. assessed the mathematical correlations between moment to force ratio and tooth movement, based on force system orientations, for 510 distinct loads. The constant of proportionality altered nonlinearly with the direction of the force, they reported, and the moment to force ratio influence on tooth movement relies on load orientations. The constant of proportionality was 12 times greater when applied parallel to the tooth's long axis than when parallel to the mesiodistal direction and 7 times higher than when parallel to the buccolingual direction (17).

Only a parabolic single-rooted tooth was found to be compatible with the Burstone formula. Due to its nonparabolic and bifurcated root shape, a maxillary first premolar cannot be calculated using the same procedure (26).

Even if the finite element method is more practicable and efficient for identifying the complicated movement pattern of orthodontics, it is still impractical to use the method on every specific patient. Finite-element analysis has the limitation of being unable to replicate the biological reaction of the osseous structures during a period of time, despite simulating the morphology and physical characteristics of the related model. Also, the results might have been impacted by initial elastic deformation of the tooth and surrounding bone. The model may not be able to determine the precise centre of resistance of a patient's dentition because it was based primarily on the average size and form of teeth; however, it has the advantage that the variables may be readily changed to get reliable results (40).

**Conclusion**

Subject to limitations of finite element method, the findings clearly show that the location of the center of resistance displaced when evaluated in different direction.

The location of CRes for buccal or lingual directions is more apical than its mesial or distal counterparts. It can therefore be concluded that canine requires a higher M/F for buccolingual translation than mesiodistal translation.

**Declarations**

**Ethical Approval and consent to participate:**

Ethics approval was granted by the Research Ethics Committee of school of Dentistry -Tehran University of Medical Sciences (approval ID: IR.TUMS.DENTISTRY.REC.1401.129)
Consent to Publication: Not applicable

Data Availability statement:
The authors confirm that the data supporting the findings of this study are available within the article.

Conflict of interest: Not applicable

Funding: Not applicable

Acknowledgment: Not applicable

Author contribution:
Elaheh Kamali wrote the main manuscript text and Allahyar Geramy, designed the study and edited the manuscript text. Amirreza Geramy analyzed the data and prepared figures 1-4. All authors reviewed the manuscript.

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**Figures**
Figure 1

Designed mandibular canine and surrounding tissues in buccal (a) and lingual (b) views.

Figure 2

Meshed model of designed mandibular canine and surrounding tissues.
Figure 3

Estimated location of mandibular canine’s CRes. a) 0 degree CRes position - proximal view. b) 0 degree CRes position- buccal view. c) 60 degrees CRes position. d) 90 degrees CRes position. e) 210 degrees CRes position.

Figure 4

Inciso-apical location of CRes in twenty-four different planes.