Three-Dimensional Analysis Using Finite Element Method of Anterior Teeth Inclination and Center of Resistance Location

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Objective: *To locate the centre of resistance of consolidated units of four and six anterior teeth during retraction.*
Methods: *Twelve three-dimensional (3D) models were designed in SolidWorks of the anterior segment with four and six teeth and their supporting structure. A proper force system was applied in each model to retract the teeth bodily. The exact location of the centre of resistances (CRes) was determined. It was found that the path of CRes change in four-tooth and six-tooth units according to the anterior teeth torque.*
Results: *A posterior shift of the CRes by increasing the inclination of teeth was shown. However, vertical position has a fluctuant behaviour. First it moves apically, then it moves incisally. Furthermore, results suggest that in en masse retraction, translation can be achieved with a smaller amount of moment-to-force ratio than in four-incisor retraction. In other words, for bodily retraction of anterior incisor segments, we should apply force in a more apical position.*
Conclusion: *Different anterior torques between 7 and 35 degrees, cannot affect the CRes position dramatically. The area of CRes shifting is 0.92 mm (anterioposteriorly) x 0.74 mm (superior-inferiorly) in the six-tooth unit in the teeth model and 0.85 mm (anterioposteriorly) x 0.82 mm (superior-inferiorly) in the teeth and bone model. In the four-tooth model, the area of CRes shifting is 0.97 mm (anterioposteriorly) x 0.93 mm (superior-inferiorly) in tooth model and 0.77 mm (anterioposteriorly) x 0.87 mm (superior-inferiorly) in the teeth and bone model.*

Key words: *3D finite element analysis, anterior teeth, centre of resistance, anterior teeth retraction, anterior tooth inclination*

Knowledge of the biomechanical principles of tooth movement is essential for the orthodontist to perform a specialised treatment plan. One of the major biomechanical considerations in orthodontics is space closure. Anterior tooth retraction represents a basic phase of fixed orthodontic treatment, because three-dimensional (3D) control of anterior teeth movement and correct positioning of the teeth are important for function, aesthetics and stability[1].

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Efficient orthodontic tooth movements mainly depend on the relationship between the line of action of the force and the center of resistance of a tooth. We have bodily tooth movement if a single force passes through the centre of resistances (CRes). On the other hand, we will have a moment tending to rotate the tooth if the force is not acting through the centre of resistance. The magnitude of such moment is presented by the product of the force magnitude, and the perpendicular distance between the line of the force and the centre of resistance. Longer moment arms produce greater rotating effects. These biomechanical principles can help us have predictable and controlled tooth movements[2].

On the other hand, the applied moment-to-force ratio on the tooth determines the type of movement, such as uncontrolled tipping, controlled tipping, bodily movement, or root thrusting. In addition, the direction and the application point of retraction force in relation to

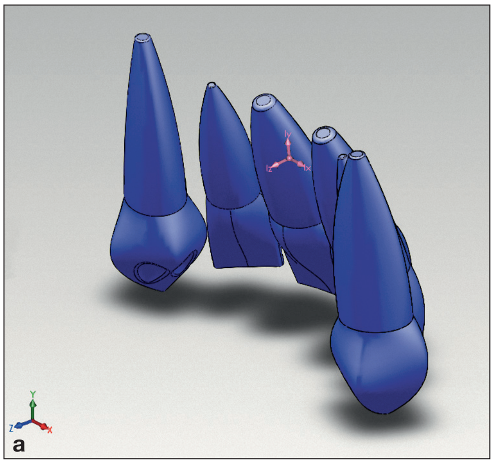

Fig 1a 3D model of the six anterior teeth without supporting structure.

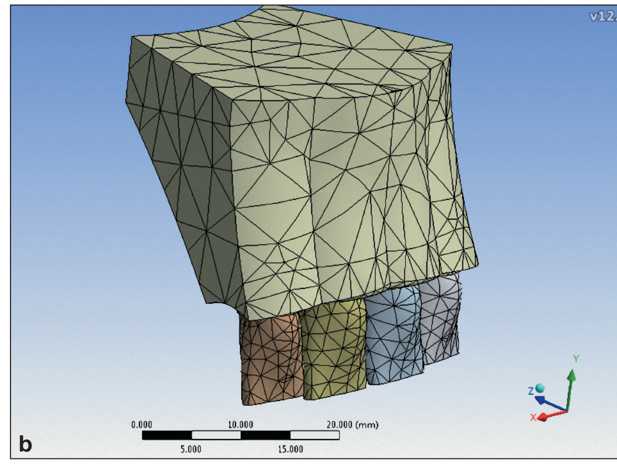

Fig 1b T3D model of the anterior teeth with supporting structure.

the location of the centre of resistance are critical factors in predicting and planning the tooth movement of anterior teeth[3].

Based on these issues, determining the CRes of the teeth is important to produce desirable movements. Many investigators have assessed the location of teeth's CRes by various methods; one method is human autopsy materials and dry skulls, for example, which was used by Pedersen et al[4] and Van den Bulcke et al[5] in their experiments. The position of the CRes was evaluated of four-teeth on human autopsy material with retractive forces by Pederson.[6] In that study, the CRes of the upper incisors was located 5 mm apical to the bracket level, which was positioned 4 mm from the incisal edge. Determination of the CRes of the upper incisors has been investigated on photoelastic models by Matsui et al[6]. Those authors stated that the CRes of the upper incisors was located 6 mm apically to the labial alveolar crest of the central incisor. Van den Bulcke et al, using the laser reflection technique on dry human skulls, observed that the CRes of the upper incisors was located 5 mm apically to the interproximal bone of the central incisors[5].

Gjessing designed a PG spring for maxillary incisors and stated that the CRes of the upper incisors was located 7 mm distally and 9 to10 mm gingivally to the centre of the lateral bracket[7,8].

However, these experiments had some disadvantages. The mechanical properties of the periodontal ligament (PDL) are changed considerably on human autopsy materials[6] or the PDL has been completely replaced by a synthetic substance with similar characteristics when using dry skulls[5]. Since results obtained from autopsy material and dry skulls are inconsistent and confusing, they cannot be applied directly to orthodontic treatment planning.

A magnetic sensor device is another method for the localization of the CRes. Yoshida et al performed a study using this method to locate the CRes of two, four and six-tooth units during retraction in two human subjects[2]. They reported that the CRes of the two- and four-incisor units were approximately at the same position, while the CRes in the six-tooth unit was more incisal[2].

In another study, Sia et al selected three human subjects with maxillary protrusion. They used a magnet sensor device to apply force. Force application was under sliding mechanics and had various heights of retraction forces. They determined the location of the CRes by calculating the angle of rotation from the displacements measured. The results showed that the location of the CRes of the maxillary central incisor was approximately 0.77 mm of the root length from the apex[9].

The finite element method (FEM), as a numerical analysis to find approximate solution to complex problems, was first introduced in aerospace industry. This method has proven its efficiencies in different fields. Three-dimensional FEM is a powerful discipline used to examine complex mechanical behaviours of dental structures. Its usefulness in designing, analysing and finding answers to dental biomechanical problems has been proven[10-15].

Materials and methods

Three-dimensional finite element and geometric analysis was used. Twelve 3D models were designed of a maxillary anterior segment and included the anterior teeth and canines, based on the average dimensions[16] in models 1 to 6 and adding supporting structures in models 7 to 12 (Fig 1). A simplified 0.25 mm thick periodontal ligament layer (PDL) was modelled based on the root-form geometry of the teeth. The models were similar except for the presence or absence of the alveolar bone. Models 1 to 6 were used in the geometric analysis and the rest were used in the finite element analysis.

SolidWorks 2010 was selected for the modelling phase. The models were designed in a top-to-bottom manner. The geometric centres of models 1 to 6 were determined using SolidWorks.

Models 7 to 12 were transferred to the ANSYS Workbench Ver. 11.0 (ANSYS) for calculations. All the vital tissues were presumed elastic, homogeneous and isotropic. The corresponding elastic properties such as Young's modulus and Poisson's ratio were determined according to recent researches[10-15] (Table 1) and were applied. Models 7 to 12 were meshed, between 21,407 and 29,568 nodes; between 11,206 and 15,658 10-node-quadratic tetrahedron body elements. As a boundary condition, all nodes at the base of the models were restrained so that all rigid body motions were prevented. The inclination of canine teeth was 7 degrees in all models, but in incisors it increased from 7 to 32 degrees for central incisors and from 2 to 27 degrees for lateral incisors. Bodily movement and intrusion of the teeth were produced, making it possible to find the exact position of the CRes in different models. The tooth movement type was determined by the displacement of the mesio-inciso-labial point angle of the upper right central incisor. In the second phase, the models without bone were evaluated in SolidWorks.

The location is reported as distances from the defined reference point. (The middle point of the distance between the upper central incisors in this study.) The findings were prepared to analyse the manner of their displacements according to the change in torque angles.

Results

Results are displayed in two parts: the first part is related to the measurements obtained from determination of the CRes in tooth groups without bone consideration; the second part is related to bone and teeth together.

Tooth model

The results showed in the teeth models that as the inclination of teeth increases to a torque of 12, 7, 7, the CRes shifted to an apical position. Then by increasing inclination it shifts to an incisal position. In an anterio-posterior position, results showed by increasing incisor inclination the CRes moves to a posterior position; in a four-tooth unit, in the inclination (7, 2, 7) the CRes position is 2.2 mm posterior to the contact of central teeth. Then by increasing the inclination it moves to a posterior position, so that in the inclination of (32, 27,7) it is in 3.17 mm posterior to the contact of central incisors.

Table 1 Mechanical Properties of the materials

	Young's Modulus (MPa)	Poisson's ratio
Tooth	20300	0.26
Spongy bone	13400	0.38
Cortical bone	34000	0.26
PDL	0.667	0.49

Tooth and bone model

By increasing inclination on the four-tooth unit model, the CRes move from 6.62 mm in the torque of (7, 2, 7) to 7.39 mm posterior to central contact in inclination of (32, 27, 7). Vertical positions of the CRes change from 19.85 mm superior to the contact of central teeth to 19.98 mm in the inclination of (12, 7, 7), then it moves incisally to 19.11 mm in the inclination of (32, 27, 7).

Table 2 represents the sagittal and vertical positions of the CRes from contact points in teeth and teeth and bone models in different inclinations. Figures 2 and 3 show the shift of the CRes between models.

Discussion

The initial study of the CRes' localisation of upper incisors during retraction was performed on a dry human skull[1].

In previous studies, labiolingual inclination was not taken into consideration as a variation during retraction. In clinical conditions, the crowns of anterior teeth are inclined labially or lingually, and the labial and palatal bone levels are mostly different with respect to the line of the retraction force, which is parallel to the occlusal plane. So, this study was designed to determine the effect of initial inclination of anterior teeth in the position of the CRes during retraction. In all conditions, in the six-tooth unit, the inclination of the canines was 7 degrees and the CRes were measured from contact point of the central incisors.

Table 2 CRes position in different torques

Torque*	Ant-post position**	Vertical position***
Teeth models Four-tooth unit 7,2,7	2.2	10.95
12, 7, 7	2.54	11.37
17, 12, 7	2.78	11.19
22, 17, 7	2.97	10.97
27, 22, 7	3.05	10.66
32, 27, 7	3.17	10.44
Six-tooth unit		
7, 2, 7	5.33	10.73
12, 7, 7	5.55	10.96
17, 12, 7	5.73	10.78
22, 17, 7	5.98	10.59
27, 22, 7	6.11	10.51
32, 27, 7	6.25	10.22
Teeth and bone model Four-tooth unit		
7, 2, 7	6.62	19.85
12, 7, 7	6.76	19.98
17, 12, 7	6.86	19.81
22, 17, 7	7.01	19.58
27, 22, 7	7.21	19.41
32, 27, 7	7.39	19.11
Six-tooth unit		
7, 2, 7	7.06	18.48
12, 7, 7	7.25	18.73
17, 12, 7	7.36	18.56
22, 17, 7	7.45	18.31
27, 22, 7	7.69	18.12
32, 27, 7	7.91	17.91

Our investigation shows that by increasing incisors' inclination, the CRes of anterior segments move to an apical position; but it should be noticed that this apically shifting continues until an inclination of (12, 7, 7); after that the CRes move to an incisal position.

In an anterior-posterior dimension, the CRes shifted to a posterior position when the incisors' torque started to increase. This result can extrapolate to a six-tooth unit; but in this complex, the CRes were more incisal and had more of a posterior position in comparison with the four-incisor unit.

This suggests that in en masse retraction, translation can be achieved with a smaller amount of moment-of-force ratio than in a four-incisor retraction. In other words, for bodily retraction of anterior incisor segments, we should apply force in an apical position.

According to our investigation, tooth and bone models also follow these scenarios. But in these models, the CRes had a more posterior and apical position in comparison to teeth models; this difference was greater in the four-tooth unit.

These findings are against some studies. Based on using human dry skulls, Van den Bulcke et al stated that the location of the CRes moved apically as anterior segments included canines[1]. Furthermore, Pederson et al reported that the CRes' location in a six-tooth unit is more apically than the four-tooth unit, using human autopsy material[4]. Melsen et al determined the CRes' location in a six-tooth unit theoretically[17]; the authors reported that the CRes are halfway between the midpoint of the four-incisor unit's centres of resistance and the canine's centre of resistance. The authors concluded that canine teeth with long roots have a significant effect in the CRes' movement to the apical.

On the other hand, Yashida et al performed an *in vivo* study with a magnet device and showed that the CRes in a six-tooth unit was significantly more incisal in comparison with a four-tooth unit[2]. He found that adding a canine to an anterior segment resulted in 0.8 to 1 mm incisal movement of the CRes. However, it should be noticed that, based on our study, inclinations of the anterior teeth have a greater role in the location of CRes. So, we suggest considering this issue in future studies.

Reviewing the result of studies in this field shows disagreement between *in vivo* and *in vitro* studies. Yashida et al believed that it may have been resulted from differences in the properties of the periodontal tissues[2]. Mechanical characteristics of the PDL change on human autopsy material, and to simulate the PDL in dry skulls, a substitution material was used in the previous *in vitro* studies, so measured tooth displacements cannot present physical distortion of the periodontium under normal conditions.

However, 3D finite element analysis and theoretical methods has limitations, because the determinations of the CRes' location in six-tooth units is influenced by the size, shape, and position of the canines[18]. Many studies confirmed that the location of the CRes can be influenced by bone support, root morphology and teeth inclination. Kusy and Tulloch[19] reported that as the root length increased and alveolar bone height decreased, the CRes shift to an apical position, which is in accordance with Pederson[4]. According to Tanne et al[20], as root length increased 50%, the CRes move 1.3 mm to the apical position, but the CRes move 4 mm to the apical if alveolar bone height decreases by 50%.

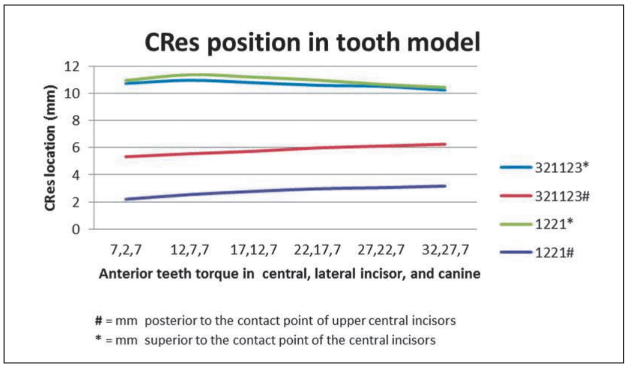

Fig 2 Shift of the CRes in tooth models; anterio-posterior and superior-inferior.

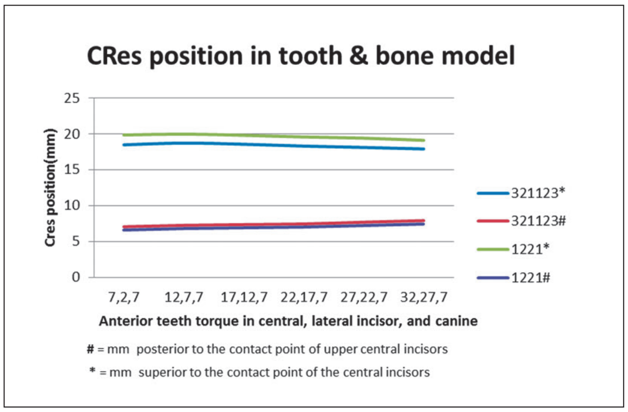

Fig 3 Shift of the CRes in tooth and bone models; anterio-posterior and superior-inferior.

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