Research Article

A Three-Dimensional Finite Element Method to Study the Changes in Centre of Resistance with Alveolar Bone Resorption

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ABSTRACT

Introduction: Patterns of initial displacement of a tooth may be influenced by variables like alveolar bone, width of periodontal ligament space, and properties of the periodontium. Alveolar bone loss modifies biomechanical behavior of a tooth under orthodontic forces. Thus it is imperative to know optimal force considerations for patients with altered alveolar bone height. The aim of this study was to locate the centre of resistance and centre of rotation of maxillary central incisor at various stages of alveolar bone loss.

Materials & Methods: A descriptive cross-sectional study design was used. The present study was conducted in the Department of Orthodontics and Dentofacial Orthopedics UCMS College of Dental Surgery, Bhairahawa. A 3-dimensional model of an upper central incisor was designed using ANSYS software in Pentium III computer. Five models of an upper central incisor with 1 mm to 8 mm of alveolar bone loss were created. The mechanical properties (Poisson's ratio and Young's Modulus) of the periodontal ligament, tooth and alveolar bone were considered. A force of 1N was applied to the labial surface of the tooth crown at each phase of the study at 5.5 mm apical to incisal edge (this was presumed to be the location of the bracket). The point of force application was centered mesiodistally.

Results: The results revealed that alveolar bone loss resulted in apical shift of the centre of resistance. The centre of resistance was at 9.3 mm from the apex of the tooth, it shifted apically to 8.8 mm, 5.7 mm, 4.9 mm and 4.4 mm with bone loss of 1 mm, 5 mm, 6.5 mm and 8 mm, respectively. A greater amount of displacements of the incisal edge and apex were observed with increased alveolar bone loss for a constant applied force. The Moment/Force ratio required to produce bodily movement increased with alveolar bone loss.

Conclusion: Alveolar bone loss led to a change in the centre of resistance as a result of alteration in bone support.

KEYWORDS: Alveolar bone, Centre of resistance, Centre of rotation, Finite Element Method

INTRODUCTION

Orthodontic biomechanics describes the biological reactions of the dental structures in the interaction with mechanical forces in orthodontics. The location of the centre of resistance is considered an essential factor in the planning of orthodontic tooth movements. With exact knowledge of the centre of resistance, the force system that must be applied to the crown of the tooth to achieve the desired tooth movement can be determined.[1]

If a tooth crown is loaded with a force couple, it will rotate around a well-defined axis, the so-called centre of resistance. This mechanical property has been used in a number of experimental and numerical studies to determine the position of the centre of resistance of single teeth, in part using highly idealized tooth models.[2,3] Different types of orthodontic tooth movement may produce different mechanical stress at varying locations within the root.

Finite element analysis is a highly precise technique used to analyze structural stress. It involves discretization of the continuum into a number of elements. Discretization is a theoretical sub-division of the structure while it remains in continuity. Finite element analysis is an approximation method that divides the entire region of the structure into a set of elements that are connected by points This method has proved effective in many dental fields, such as simulation of tooth movement and optimization of orthodontic mechanics. The characteristics of the periodontium make the finite element analysis the most suitable means of analysis because of its ability to handle various shapes and material inhomogeneity.[4]

In orthodontics, finite element analysis has been used successfully to model the application of forces to single tooth systems. Ever since the Andrews straight wire appliance was introduced commercially, many new bracket prescriptions and techniques have been developed and modified as treatment mechanics progress to create a force system that can work efficiently and shorten the orthodontic treatment period. A good knowledge in biomechanics will help the clinician to apply force in a balanced fashion within the physiological limits that bring about favorable tooth movement. The objectives of the present study were to evaluate the changes in centre of resistance and centre of rotation of maxillary central incisor with varying bone loss.

MATERIAL AND METHODS

The present study was conducted in the Department of Orthodontics and Dentofacial Orthopedics, Universal College of Medical Sciences, College of Dental Surgery, Bhairahawa. Technical support was taken from Tejvi technical institute, Banguluru, India.

ANSYS software version 13 (ANSYS Inc. USA) in Pentium III computer was used to prepare maxillary central incisor models for the study. The sample comprised five 3-dimensional models of maxillary central incisor. (Figures: 1-9) Each model contained 529657 to 445510 elements and 95544 to 82447 nodes depending upon the amount of alveolar bone loss. The geometry of 3-dimensional finite element model of maxillary central incisor was created by manually designing the tooth morphology, periodontal ligament and alveolar bone according to the dimensions and morphology found in Wheeler's Dental Anatomy Physiology and Occlusion[5] (Figures 1 to 4).

The height of the central incisor (distance from apex of the root to the incisal edge) was 23.5 mm and the mesio-distal and labio-palatal widths of the crown were 8.5 mm and 7 mm respectively (Figures 1 & 2). The normal root length was 13 mm and the normal bone height was 13 mm. The periodontal ligament (PDL) was simulated as 0.2 mm thick layer around the root. In the present study, all materials were assumed to be isotropic and elastic. The mechanical properties (Poisson's ratio and Young's Modulus) of the PDL, tooth and alveolar bone were obtained from previous studies[6,7] (Table 1).

The boundary conditions were defined to simulate how the model was constrained and to prevent it from free body motion. A force of 1 N was applied to the labial surface of the tooth crown at each phase of the study, at 5.5 mm apical in respect to the incisal edge. This was presumed to be the location of the bracket. The point of force application was centered mesio-distally. Congruence of the line of action of the force with the long axis of the tooth avoids any rotation tendency at the models, due to the lack of any moment arm with respect to the tooth long axis.

Student t- test was performed to analyze the effects of changes in centre of resistance and centre of rotation with various levels of bone loss at the significance of $p < 0.05$. Linear regression analysis was done to study the relationship between bone loss with changes in centre of resistance and centre of rotation respectively.

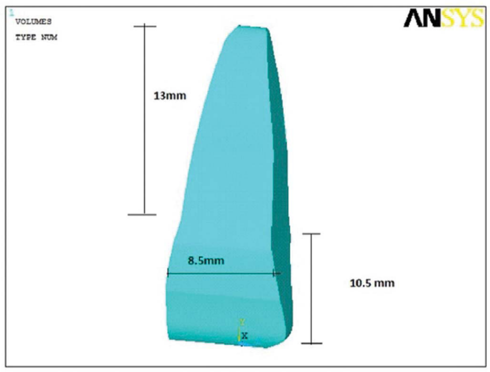


Fig 1: Central Incisor measurements frontal view

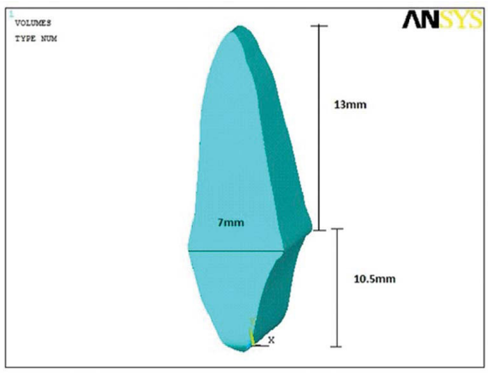


Fig 2: Central Incisor measurements lateral view

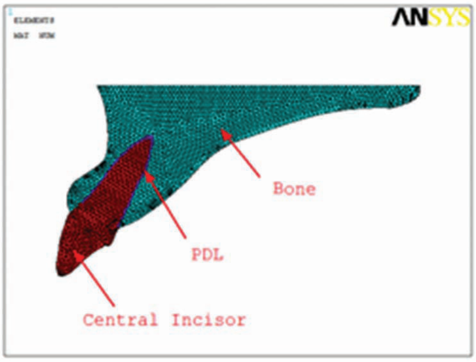


Fig 3: Central incisor model with periodontal ligament and alveolar bone

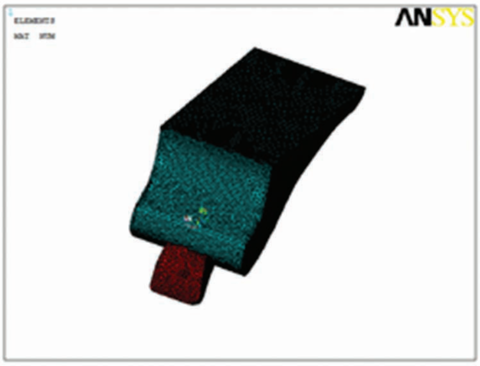


Fig 4: An Isometric view of a 3-dimensional model used in the study

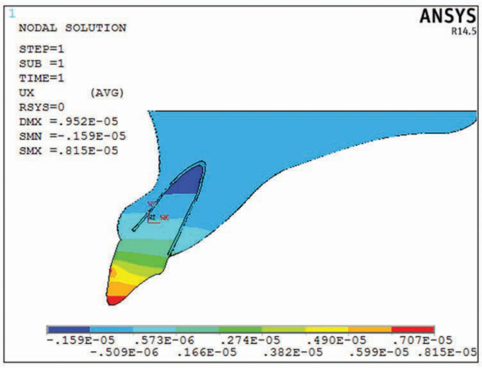


Fig 5: 3-dimensional model of central incisor with 13 mm alveolar bone height

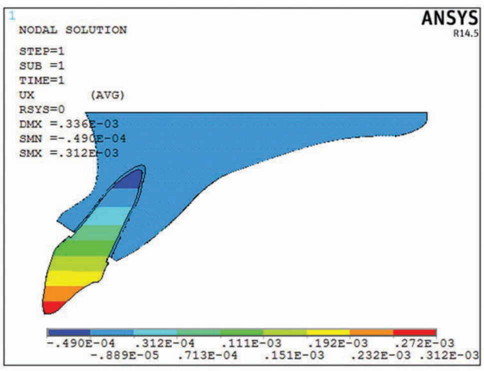


Fig 6: 3-dimensional model of central incisor with 12 mm alveolar bone height

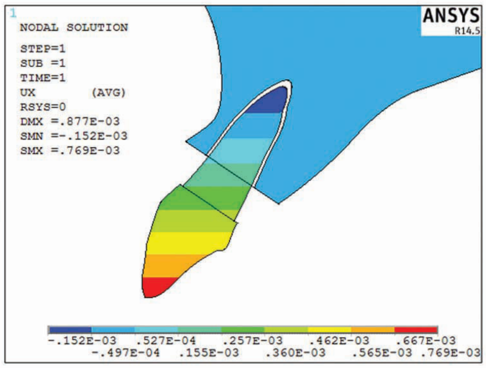


Fig 7: 3-dimensional model of central incisor with 8 mm alveolar bone height

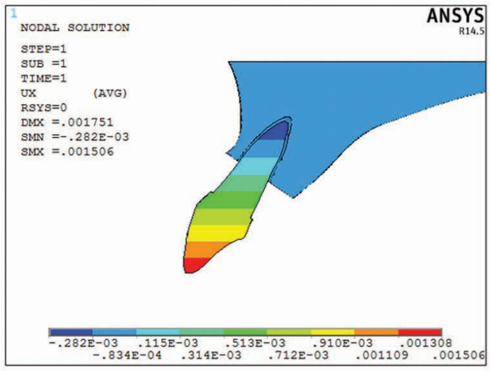


Fig 8: 3-dimensional model of central incisor with 6.5 mm alveolar bone height

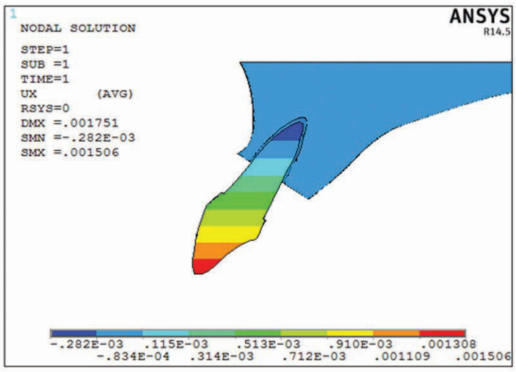


Fig 9: 3-dimensional model of central incisor with 5 mm alveolar bone height

RESULTS

This study found that with alveolar bone loss, the centre of resistance shifted towards the apex. The distance between the crest of the alveolar bone and the center of resistance also decreased with alveolar bone loss. Table 2 shows that the centre of resistance of the tooth at 9.3 mm from apex, shifted apically to 8.8 mm, 5.7 mm, 4.9 mm and 4.4 mm with bone loss of 1 mm, 5 mm, 6.5 mm and 8 mm respectively. The change in the centre of resistance was statistically significant.

Table 3 shows that the centre of resistance was 3.7 mm from the crest of the alveolar bone with normal alveolar bone height, and it decreased to 0.6 mm for 8 mm of alveolar bone loss. The centre of rotation lies apical to the centre of resistance by a small distance in healthy periodontium. With a decrease in alveolar bone height, the centre of rotation is shifted apically. The centre of rotation in healthy periodontium was at 8.5mm. It decreased to 7.4 mm, 4.1 mm, 3.8 mm and 3.6 mm with an alveolar bone loss of 1 mm, 5 mm, 6.5 mm and 8 mm, respectively, as shown in Table 2. The changes in the centre of rotation were statistically significant as shown in Table 4.

Table 5 shows that the M/F ratio to obtain bodily movement was 8.7 in normal alveolar bone height. It increased to 13.6 with bone loss of 8 mm. The M/F ratio increased by 6.45%, 41.37%, 50% and 56.32% with bone loss of 1 mm, 5 mm, 6.5 mm and 8 mm, respectively. The change in the M/F ratio was statistically significant.

The stress pattern after application of the same amount of force increased as shown by this study. Table 6 shows that the amount of incisal edge displacement increased by 33 times and apex displacement increased by 26.25 times compared to normal bone height. The cervical displacement also increased by 51 times as compared to normal bone height, with 8 mm of bone loss.

As shown in figures 10 and 11, based on statistical analysis a regression equation was derived for the centre of rotation and the centre of resistance. Using this equation, the centre of resistance and the centre of rotation can be approximately located for any variation in alveolar bone height.

Table 1- Mechanical properties for the structural elements[6,7]

Material	Young's Modulus (kg/mm^2)	Poisson's Ratio
Tooth	2 x 10	0.30
PDL	6.8 x 10	0.49
Alveolar Bone	1.4 x 10	0.30

Table 2- Characteristics of the model used in the study of the central incisor

Model	Bone height (mm)	Number of elements	Number of nodes	Centre of resistance from tooth apex (mm)	Centre of rotation from tooth apex (mm)
1	13	529657	95544	9.3	8.5
2	12	522264	94292	8.8	7.4
3	8	480766	87277	5.7	4.1
4	6.5	462954	84201	4.9	3.8
5	5	445510	82447	4.4	3.6

Table 3- Exact location of the centre of resistance with various bone heights

Alveolar bone loss (mm)	Alveolar bone height (mm)	Centre of resistance from alveolar crest (mm)
0	13	3.7
-1	12	3.2
-5	8	2.3
-6.5	6.5	1.6
-8	5	0.6

Table 4- Association of alveolar bone loss with the central incisor parameters

Study parameters	Normal	Alveolar Bone loss Mean ±SD	% Change	Significance
Centre of resistance	9.3	5.95 ± 1.97	36.02	0.042*
Centre of rotation	8.5	4.77 ± 1.78	44.04	0.025*
Number of elements	529657	477873.50 ± 32908.31	9.78	0.051
Number of nodes	95544	87054.25 ± 5221.82	8.88	0.047*
M/F ratio	8.7	13.35 ± 0.35	-53.45	0.034*

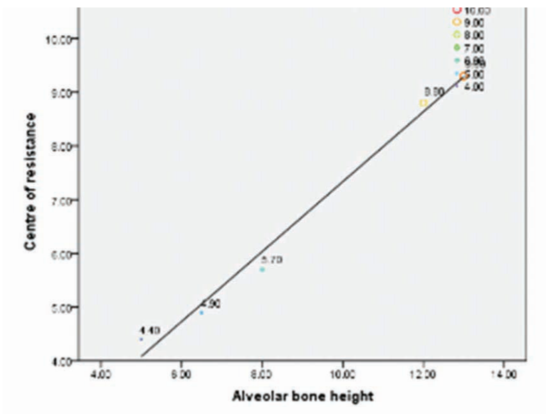
*Statistically significant ($p < 0.05$)

Table 5- M/F ratio to maintain bodily movement with different alveolar bone heights

Alveolar bones loss (mm)	0	-1	-5	-6.5	-8
M/F ratio	8.7	9.2	12.3	13.1	13.6
M/F ratio increment (%)	-	6.45	41.37	50	56.32

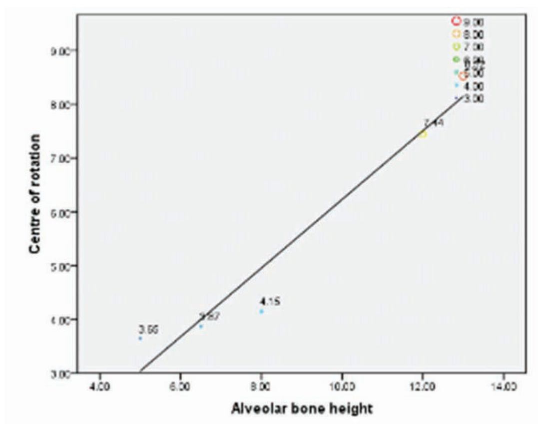
Table 6- Change of the movements in different parts of an upper central incisor due to the alveolar bone loss

Bone loss (mm)	Incisal edge movement (mm)	Relative movement	Cervical part movement (mm)	Relative movement	Apical part movement (mm)	Relative movement
0	0.0075	1	0.0017	1	0.0016	1
-1	0.0106	1.41	0.0030	1.76	0.0026	1.62
-5	0.040	5.3	0.014	9.3	0.0058	3.62
-6.5	0.098	13	0.033	22	0.019	11
-8	0.25	33	0.088	51	0.042	26.25



Centre of resistance =
0.8295 + 0.6506 X alveolar bone height

Fig 10: Linear Regression analysis showing association of the center of resistance with the varying alveolar bone height in Central Incisor



Centre of rotation =
-0.5835 + 0.704 X alveolar bone height

Fig 11: Linear regression analysis showing association of the center of rotation with the varying alveolar bone height in Central Incisor

DISCUSSION

When orthodontic force is applied to a tooth, stress is distributed throughout the periodontal ligament and reaches a state of equilibrium within 2 minutes[7]. Biologic responses such as bone resorption and apposition follow in response to strain in the periodontal ligament. An instant tooth movement within the periodontal ligament is called a primary displacement, whereas the movement followed by a biologic response is called a secondary displacement. The exact relationship between these 2 types of tooth movement is compounded by biologic variation. Nevertheless, secondary displacement can be predicted by the primary tooth movement that, in turn, can be determined by analyzing the stress distribution pattern in the periodontal ligament[8].

Uniform strain should be found along the compression site to allow the teeth to be translated. The location of force at which the tooth is translated is defined as the centre of resistance. The position of the centre of resistance is influenced by alveolar bone loss or apical root resorption and by the variable shape of the root.

Alveolar bone loss can modify the biomechanical behaviour of a tooth when subjected to orthodontic forces. The present study showed that there was greater displacement of the apex, which can lead to root resorption and excessive injury to the periodontal ligament, resulting in tooth mobility. It was seen that as the alveolar bone loss occurred, the centre of resistance shifted more apically. In this study, the centre of resistance of a tooth with normal bone height was found to be at 9.3 mm from the apex of the root. Burstone[2] reported that the centre of resistance was located at a point 0.60 times the root length from the apex on a 2-dimensional theoretical model based on a parabolic root shape and at 0.67 of the root length on a 3-dimensional model, whose root geometry was approximated to a paraboloid of revolution. Thus, the location of the centre of resistance has been simply represented by the proportion of the root length measured from the root apex to the alveolar crest. Likewise, Nikolai8 determined the location of the centre of resistance at 0.45 of the root length with a 2-dimensional model for theoretical analysis. Using finite element models, Tanne et al9 and Vollmer et al[10] determined the locations of the centre of resistance at 0.76 and 0.58 of the root length for a maxillary central incisor and canine, respectively. Meyer and Katona[11] compared the locations of the centers of resistance in the buccolingual and mesiodistal directions of the mandibular central incisors of 6 dogs and found locations of centre of resistance were between 43% and 51% of root length in buccolingual direction and between 31% and 43% of root length in mesiodistal direction.

In the present study, the centre of resistance was found to be located at 3.2 mm, 2.3 mm, 1.6 mm and 0.6 mm from the alveolar crest with bone loss of 1 mm, 5 mm, 6.5 mm and 8 mm respectively. This is in line with the results of another study done by Geramy[12] on maxillary central incisor with various alveolar bone heights who found the locations of centre of resistance at 5.44 mm, 4.57 mm, 3.72 mm, 2.65 mm, 1.94 mm and 1.48 mm with alveolar bone heights of 13 mm, 12 mm, 10.5 mm, 8 mm, 6.5 mm and 5 mm respectively.

The location of the centre of resistance is important because, when there is a variation in the alveolar bone height due to periodontal disease, there is a shift of the centre of resistance more to the apical region, making the use of smaller orthodontic force mandatory. As the centre of resistance shifts apically, a given force will generate a large moment. The magnitude of force applied should be manipulated accordingly to avoid the undesirable consequences. A clinical study by Boyd et al[13] reported a slight loss of periodontal attachment in adults or adolescents during treatment with fixed orthodontic appliances. This results in an increased crown-to-root ratio, thus increasing the amount of stress in the periodontium, causing periodontal injury.

The centre of rotation of the tooth with healthy bone support was 8.0 mm from the apex. The centre of rotation was located at 7.44 mm, 4.15 mm, 3.87 mm and 3.65 mm from the apex with alveolar bone loss of 1 mm, 5 mm, 6.5 mm and 8mm, respectively. A similar study by Tanne et al[14] showed apico-gingival levels of centre of rotation from a single force ranging from 5.4 mm to 2.3 mm apical to alveolar crest, in the cases of the alveolar bone height being varied from 13 mm to 6.5 mm, respectively.

The present study showed that the centre of rotation is apical to center of resistance, and with alveolar bone loss, it shifted more apically. So, for a desired tooth movement, it is important to predict the location of the centre of rotation and centre of resistance so that undesirable tooth movements can be controlled. The present study also demonstrated that the displacement of the tooth apex increased with shorter root length. Based on statistical analysis, a regression equation was derived for the center of resistance and centre of rotation. Using these equations, we can approximately locate centre of resistance and the center of rotation with further variation in root length.

This study also showed that the M/F ratio to obtain bodily movement was 8.7. The M/F ratio increased by 6.45%, 41.37%, 50% and 56.32% with alveolar bone loss of 1 mm, 5 mm, 6.5 mm, 8 mm, respectively. These results were almost similar to a study designed by Geramy[12]. The M/F ratio increased from -8.44 (no bone loss) to -12.46 (8mm of alveolar bone loss). Tanne et al[14] studied the effect of alveolar bone loss on the M/F ratio for bodily movement of a maxillary central incisor with 13.0mm root length using a 3-D finite element model. According to their results, the M/F ratio increased from 10.7 (normal alveolar bone height) to 12.3, 13.9, and 15 for 2.5 mm, 5.0 mm, and 6.5 mm alveolar bone loss. Siatkowski[15] reported an increase of 38% of M/F ratio needed to produce bodily movement when 5 mm of marginal alveolar bone loss occurred; this study found 41.37% for the same condition.

The stress pattern after application of the same amount of force increased with bone loss as shown by the present study. The amount of incisal edge displacement increased by 33 times and apex displacement increased by 26.25 times compared to normal alveolar bone height. A similar result was obtained by Tanne et al[14] in a study conducted on maxillary central incisors with various levels of alveolar bone loss. The displacement of the tooth at the incisal edge increased from 2.3 to 6.9 and then to 16.5 times with approximately 19%, 38% and 50% alveolar bone loss when compared with a tooth with normal alveolar bone height. In a similar study conducted by Geramy[12] on maxillary central incisor with various alveolar bone heights, the displacement of the tooth at the incisal edge increased from 1.46 to 44.2 times with approximately 8% to 61% alveolar bone loss. However, the findings of Cobo et al[16] are dissimilar to the present study, in which, with alveolar bone loss, centre of resistance was located above the alveolar crest.

The limitations of our model include approximation in the material behavior and shapes and morphology of the tissues. There are wide variations in morphologic conditions such as crown height, shape of the roots, length of the root and bone thickness among normal individuals, but the morphology of the tooth described in this study represents the most common morphologic features of a maxillary central incisor, which may affect the generalizability of the analysis. The PDL was modelled as a layer of uniform thickness of 0.2mm and was treated as linear-elastic and isotropic, even though the PDL exhibits anisotropy and nonlinear viscoelastic behaviour because of tissue fluids. In periodontally compromised patients, PDL properties may vary significantly with time due to the continuous remodelling process. The tooth was simplified as a homogenous body because force transmission to the PDL is not significantly affected by adding the internal structure, because of its greater stiffness relative to the PDL. Limitations of the study may be improved by utilizing advanced imaging, such as a microCT scan to create highly detailed 3D models and utilizing more efficient software to get more accurate results. The effect of bone and the PDL on the stress in the periodontium should be examined in future studies.

CONCLUSIONS

This study concluded that as the alveolar bone height decreased, the centre of resistance and centre of rotation shifted more apically. The amount of tooth displacement increased with alveolar bone loss. The M/F ratio needed for bodily tooth movement also increased with alveolar bone loss.

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