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Original Research Article

A three dimensional finite element analysis of apical stress distribution during intrusion of maxillary central incisor with different inclinations in labial and lingual appliance systems

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ABSTRACT

Background: The objective of this study was to evaluate apical stress distribution during intrusion of the maxillary central incisor with different inclinations in the labial and lingual appliance systems using a three-dimensional finite element model.

Materials and Methods: The three-dimensional finite element models of the maxillary central incisor were produced with 25 ° (normoclined), 30 ° (proclined), and 20 °(retroclined) inclinations. Each incisor model was subjected to an intrusive force of 15cN. The stress level at the apex was calculated in terms of maximum principal stresses.

Result: The stress distribution at the apex and cervix was lower in the labial compared to the lingual appliance system for the maxillary central incisor models with an inclination of 25° (normoclined) and 30° (proclined). Whereas the maxillary central incisor model with 20° (retroclined) inclination in the lingual appliance system showed the maximum stress in the cervical region.

Conclusion: During intrusion, no significant differences in stress patterns were seen at the root apex in normoclined and proclined maxillary central incisor models in either of the appliance systems, except for the retroclined central incisor model which showed maximum stresses in the cervical region.

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1. Introduction

Orthodontic tooth movement is essentially a phenomenon of the periodontal ligament (PDL). It is a bony response mediated by the PDL when prolonged pressure is applied.[1] It is achieved by remodeling processes of the alveolar bone, which are triggered by changes in the stress/strain distribution.[2] Stress-strain distribution within the periodontal ligament, resulting from orthodontic loading, is an initiating factor for orthodontic tooth movement.[3]

Different types of tooth movement may produce different mechanical stress at varying locations within the root.[4] The orthodontic displacement of a tooth is the result of a mechanical stimulus, generated by a force applied to the crown of a tooth, being turned into biological reactions. This transformation involves all the processes of mechanotransduction typical of bone modeling and remodeling, mechanocoupling, biomechanical coupling, cell-to-cell signaling, and effector response.[5]

Intrusion is one of the common forms of tooth movement that has been suggested as a potential cause of root resorption. When an intrusive force is applied to the crown, the tooth apex and associated periodontium may experience relatively high compression stresses. Owing to the capacity of such high rates of tension, an intrusion is a technique that may theoretically raise the risk of apical root resorption.[6]

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When a single intrusive force is applied to the labial surface of the anterior tooth during conventional mechanics, the tooth will not translate but tend to rotate around the center of resistance by generating a moment that results in flaring of the normoclined tooth or excessive flaring of the proclined tooth or lingual tipping of the retroclined tooth.

Most labial orthodontics are explained by theoretical and experimental biomechanical analyses; however, biomechanical principles of lingual orthodontics are rarely introduced. Due to the anatomic variations and the difficulty in direct access to the lingual surface, the lingual technique is considered more difficult than the labial one. It is well known that precise bracket positioning is the key factor in successful orthodontic treatment, particularly if more treatment is incorporated into the brackets.[7]

Burstone proposed that between load application and the beginning of alveolar bone remodeling the tooth is in equilibrium under the action of crown and root force systems. He assumed the reactive periodontal force system was linearly distributed along the root from apex to the point of cervical attachment and that the location of the change in sense of the normal distribution from tension to compression or vice versa corresponded to the position of the center of rotation along the long axis.[8] Several researchers attempted to relate tooth movement to the load applied, developing theories based on experiments that were very simple and imprecise. However, since that time, these experiments were mostly based on animal subjects. Therefore, this kind of approach could only lead to crude results in terms of probable biomechanical consequences for humans because animal tissues are often poorly reflected in human morphology and biomechanics.

For any orthodontic tooth movement, it is necessary to know the amount of stress generated by the application of forces.[9] This can be evaluated using various methods, such as the photoelastic method, finite element method, etc. The finite element method has various advantages over the other approaches. These include the heterogeneity of the tooth material, the irregularity of the tooth contour in the model design, and the relative ease of application of loads at various directions and magnitudes for a more comprehensive analysis.[10] The present study used the finite element model to describe the force system and displacement patterns generated by the intrusion of the maxillary central incisor with different inclinations in the labial and lingual appliance systems.

2. Materials and Methods

Three-dimensional finite element models of a normoclined, proclined, and retroclined maxillary central incisor were created using a human dry skull with intact maxillary dentition, and the stresses from intrusive tooth movement were determined. A laser scan (REXCAN III 3D White Light Scanner) of the maxilla was obtained with proper placement of all teeth & jaws (Figure 1). A slice of the central incisor was taken from the complete model for this study and labial & lingual brackets were positioned on models of central incisor with different inclinations (Figures 2 and 3).

2.1. *Steps involved in finite element modelling*

1. Construction of the geometric model.
2. Conversion of the geometric model to a finite element model.
3. Material property data representation.
4. Defining the boundary condition.
5. Force application using a rigid element.
6. Interpretation of results.

2.2. *Construction of the geometric model*

The mathematical model showed the biological properties of the teeth and periodontium. This was represented in terms of points (grids), lines, surfaces (patterns), and volume (hyperpatches). In this study, a laser scan of the adult maxilla was taken. The software used for geometric modeling was SolidWorks Software 2013. The geometrical models of the maxillary central incisors were developed based on the dimensions and morphological data derived from Wheelers Dental Anatomy, Physiology, and Occlusion.[11] An average PDL and bone thickness were taken as 0.25 mm and 2mm respectively, around the model of the root.

2.3. *Conversion of the geometric model to finite element model*

This geometric model was converted to a finite element model using Altair HyperMesh Software (Altair Hyperworks, Altair Engineering Inc., Troy, Michigan, USA). Tetrahedral elements were created on this CAD model and the mesh was generated. A finite element mesh was divided into several subunits called elements, which were connected at a finite number of points called nodes (Table 1). The total number of nodes and elements in the models were 59,368 and 235,146, respectively. Meshed models of maxillary central incisor with labial and lingual appliance systems are shown in Figure 4.

2.4. *Material property data representation*

The different structures involved in this study include the enamel, dentin, and pulp; periodontal ligament; and cancellous bone. Each structure has its specific material properties. Material properties were assigned to different structures such as alveolar bone, enamel, dentin, and pulp in the finite element model. The material properties assigned in this study are consistent with the data available from previous studies.[12] (Table 2).

2.5. *Defining the boundary condition*

The boundary conditions were defined to simulate how the model was constrained and to prevent the free movement of the body. The nodes attached to the area of the outer surface of the bone were fixed in all directions to avoid free body movement of the tooth.

2.6. *Force application using a rigid element*

Force application by CAD was performed using an archwire that fits into the slot of the bracket. The surface of the bracket slot was therefore used to apply orthodontic forces. Rigid elements are used to define constraint conditions, such as fixed joints, loads, and fixed supports. The master node and the slave node determine the constraint condition of the element. Force is applied at a single point and there are several nodes on the slot of the bracket. Thus, the rigid element was used to connect all the nodes on the bracket slot to a single node. The intrusive force of 15cN was applied to the surface, assuming the base of the bracket, on the labial and lingual crown surfaces, which are normally applied in clinical practice (Figure 5).

2.7. *Interpretation of results*

Stress and displacement patterns were presented as different color bands of varying magnitude. The red column of the spectrum indicated the maximum stress level followed by orange, yellow, green, and blue represented the minimum level of stress.

3. Results

The intrusive force of 15cN was loaded parallel to the teeth and the stress generated can be found in Table 3. In this case, the maximum amount of stress on the application of intrusive force to the respective finite element models of the maxillary central incisor was noted throughout the tooth and PDL. The principal stresses showed up at the alveolar crest area.

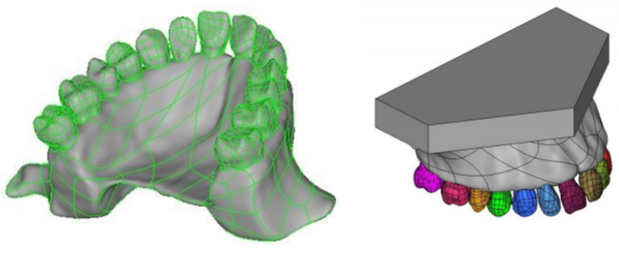

Fig. 1: Scan of the maxillary dentition

In Figures 5 and 6 by observing the labial and lingual appliance systems during the application of force, we found that the stress distribution at the apex and cervix was

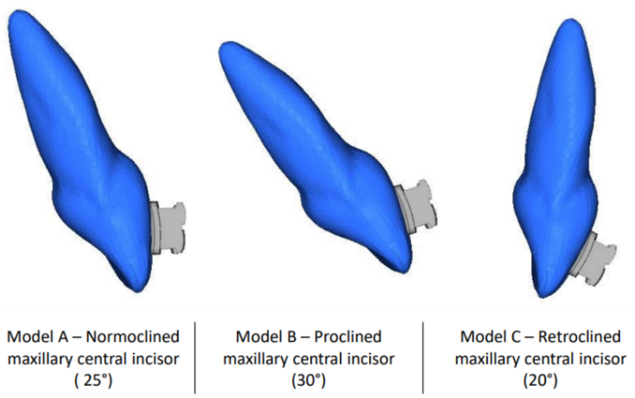

Fig. 2: Finite element models of maxillary central incisor in the labial appliance system.

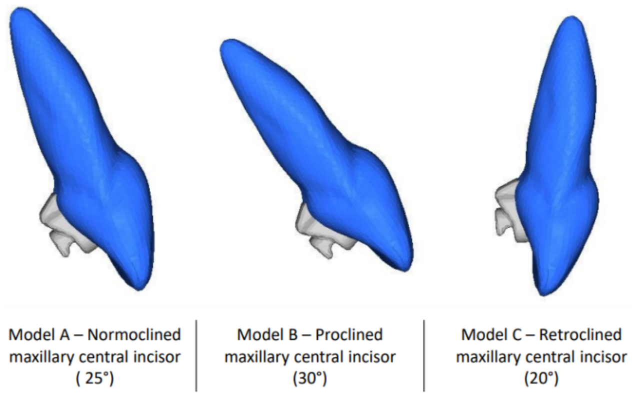

Fig. 3: Finite element models of maxillary central incisor in the lingual appliance system.

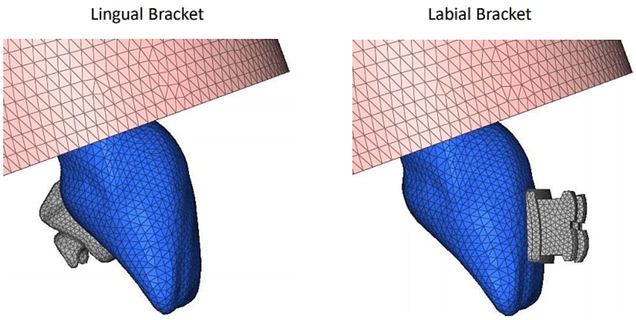

Fig. 4: Meshed models of maxillary central incisor with labial and lingual appliance systems.

Table 1: The number of nodes and elements used in this study.

Models	No. of Nodes		No. of Elements	
	Labial	Lingual	Labial	Lingual
Model A – Normoclined maxillary central incisor (25°)	9315	10486	35670	42754
Model B – Proclined maxillary central incisor (30°)	9341	10512	35964	42778
Model C – Retroclined maxillary central incisor (20°)	9271	10443	35348	42632

Table 2: Material properties used in FEM study.

	Young's Modulus (MPa)	Poisson's Ratio
Enamel	8.41×10^4	0.33
Dentin	1.83×10^4	0.30
PDL	6.90×10^{-1}	0.45
Bone	1.37×10^4	0.30

Table 3: Comparison of the magnitude of stresses (in MPa) during intrusive force.

Models	Labial Appliance	Lingual Appliance
	Intrusion	
Model A – Normoclined maxillary central incisor (25°)	0.087	0.032
Model B – Proclined maxillary central incisor (30°)	0.082	0.036
Model C – Retroclined maxillary central incisor (20°)	0.092	0.028

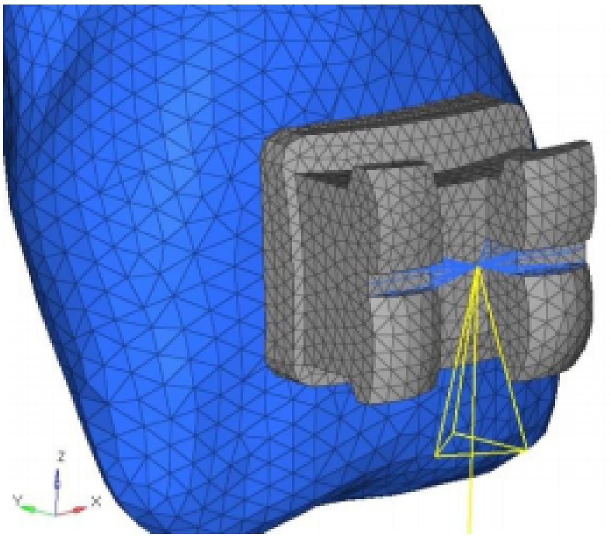

Fig. 5: Application of intrusive force.

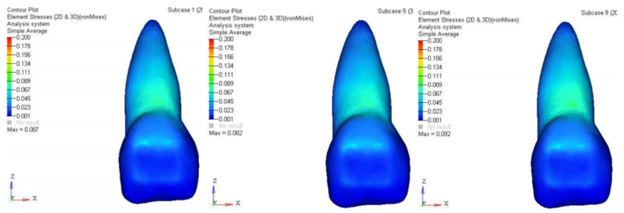

Fig. 6: The pattern of stress distribution in the labial appliance system in normoclined, proclined, and retroclined models (left to right).

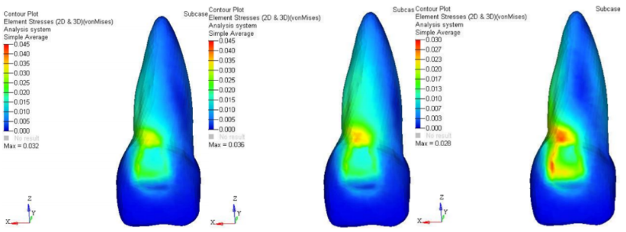

Fig. 7: The pattern stress distribution in the lingual appliance system innormoclined, proclined, and retroclined models (left to right).

lower in the labial as compared to the lingual appliance system for the maxillary central incisor model with the inclination of 25° (normoclined) and 30° (proclined). Whereas the maxillary central incisor model with 20° inclination (retroclined) in the lingual appliance system showed the maximum amount of stress in the cervical region.

4. Discussion

During tooth movement, the periodontal ligament (PDL) experiences relatively high stress on the application of orthodontic forces.[1] Maxillary central incisor was chosen because, during orthodontic treatment, it is usually subjected to orthodontic forces for prolonged periods; and since most studies have shown that apical root resorption occurs primarily in the anterior teeth, the maxillary teeth are more severely affected than the mandibular teeth.[13,14]

According to Sameshima & Sinclair,[15] maxillary teeth are affected more severely by a factor of nearly 2 than mandibular teeth, with incisors showing more resorption than canines within the arch. Secondly, the most severely resorbed teeth are maxillary lateral incisors, followed by maxillary central incisors, maxillary canines, mandibular canines, mandibular central incisors, and mandibular lateral incisors.

As the study focused on stress distribution in an apical region, along with the PDL, the maxillary central incisor model was recreated to represent the exact geometry of the root apex with normal morphology. The stress distribution in the finite element model was represented, depending on the force magnitude, by color-coding ranging from red to blue with areas of maximum stress showing up as red; and areas of minimal stress showing up as blue. The values for the maximum and minimum stress areas will vary with each figure. When the force is applied, the stress is dissipated in the alveolar crest areas and the middle of the root areas before it reaches the apex. Significant stress is therefore not observed in apical regions.

Also, differences between labial and lingual techniques have a significant impact on the biomechanics of lingual orthodontics. The relationship between the point of force application and the center of resistance is different between labial orthodontics and lingual orthodontics due to the different positions of the brackets. Because the distance between the center of resistance and the point of force applied in lingual orthodontics is smaller than in labial orthodontics, so are the moments of force. These differences between the labial and the lingual techniques can influence even small movements of the teeth.[16]

The biomechanics of intrusion may vary with the inclination of the teeth, therefore it was decided to check the effect of intrusive forces at three different incisors inclinations (normoclined, proclined, and retroclined). The recommended intrusive force for a single maxillary central incisor varies between 10 gm (10 cN) and 20 gm (20 cN) by various authors.[17] Therefore, the decision was taken to estimate the effect of 15 cN of intrusive force on the supporting structures of the central incisor to achieve intrusion, without causing any damage to the periodontium and surrounding bone.

Any type of intrusive force produces maximum stress at the apex. In this study, the maximum amount of stress was observed when the calculated resultant force was applied to 15 cN of intrusive force in all six finite element models of the maxillary central incisor.

There was no significant difference in stress patterns in Model A and Model B of labial and lingual appliance systems in the apical area. Model C of the labial appliance system showed that the maximum stresses achieved were in the cervical area. The maximum amount of stress in the cervical region of the retroclined model was also shown in the lingual appliance system. The stress distribution near the apex and cervix was maximum in maxillary central incisor models in the lingual appliance system compared to the labial appliance system.

Field et al. found that the apical site coincided with both compressive and tensile stresses.[18] The frequency of the highest compressive stress in the apical region and the maximum tensile stress in the cervical area of the inclined incisor can be clarified by the direction of the force. Inclination leads to an increased intrusive force parallel with the long axis of the tooth which leads to increased compressive stress at the apex and PDL tension in the longitudinal direction.

Wojciech Ryniewicz et al[19] performed a study to determine the stress distribution in the maxillary central incisor during intrusion by using the finite element method. The stress values indicated that there were no tissue overloaded areas. The stress distribution was regular in the periodontal ligament. Slight movements were observed with maximal values in the area of the apex. This study simulation proves that tissues surrounding the tooth were influenced mechanically by the force loaded on the bracket.

To ensure uniformity in the selection of the normal values in the present analysis, an inclination of 5° less than normal was considered to be retroclined and an inclination of 5° more than normal was considered to be proclined.

This study attempted to compare the amount of stress distribution in the apical region of the maxillary central incisor tooth following the application of intrusive forces, and this can be used to relate the susceptibility of that tooth for root resorption after applying these forces.

5. Conclusion

Lingual and labial dynamics can often contribute to very different stress behaviors and, ultimately, tooth movements. In response to orthodontic forces, the 3-dimensional finite element procedure is useful in assessing stress in and around a tooth. According to previous studies, the maximum level of relative stress at the apex of the maxillary central incisor occurred with the intrusion.

In this study, no significant differences in stress patterns were seen at the root apex in normoclined and proclined maxillary central incisor models during intrusion in either of the appliance systems, except for the retroclined central incisor model which showed maximum stresses in the cervical region.

6. Authors' Contributions

SS was the major contributor in writing the manuscript, contributed to the design of the study. VS and SA were the supervisors and had interpreted the outcomes of the data. All authors read and approved the final manuscript.

7. Abbreviations

PDL: Periodontal Ligament, cN: centiNewton, MPa: Megapascal, CAD: Computer-Aided Designed

8. Conflicts of Interests

The authors declare that they have no conflicts of interest.

9. Source of Funding

No sources of funding were used.

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