Original Article

A Finite Element Model of Apical Force Distribution From Orthodontic Tooth Movement

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Abstract: This study was undertaken to determine the types of orthodontic forces that cause high stress at the root apex. A 3-dimensional finite element model of a maxillary central incisor, its periodontal ligament (PDL), and alveolar bone was constructed on the basis of average anatomic morphology. The maxillary central incisor was chosen for study because it is one of the teeth at greatest risk for apical root resorption. The material properties of enamel, dentin, PDL, and bone and 5 different load systems (tipping, intrusion, extrusion, bodily movement, and rotational force) were tested. The finite element analysis showed that purely intrusive, extrusive, and rotational forces had stresses concentrated at the apex of the root. The principal stress from a tipping force was located at the alveolar crest. For bodily movement, stress was distributed throughout the PDL; however, it was concentrated more at the alveolar crest. We conclude that intrusive, extrusive, and rotational forces produce more stress at the apex. Bodily movement and tipping forces concentrate forces at the alveolar crest, not at the apex. (*Angle Orthod* 2001;71:127–131.)

Key Words: Stress analysis; Loading; Orthodontic forces

INTRODUCTION

The application of external forces to the teeth to produce orthodontic tooth movement carries some calculated risks. One of these is irreversible root resorption. The types of orthodontic movement that have been reported to increase the risk of root resorption include intrusion and tipping, as well as bodily movement into the lingual cortical plate of the maxilla.[1–3] Different types of orthodontic tooth movement may produce different mechanical stress at varying locations within the root.[4] In vivo measurement of stress is difficult at best; thus, development of an effective model for this system is a worthy goal.

The finite element method (FEM) is a highly precise technique used to analyze structural stress. Used in engineering for years, this method uses the computer to solve large numbers of equations to calculate stress on the basis of the physical properties of structures being analyzed.[5] FEM has many advantages over other methods (such as the photoelastic method), highlighted by the ability to include heterogeneity of tooth material and irregularity of the tooth contour in the model design and the relative ease with which loads can be applied at different directions and magnitudes for a more complete analysis. Finite element analysis has been used in dentistry to investigate a wide range of topics, such as the structure of teeth,[5–8] biomaterials and restorations,[9–11] dental implants,[12–15] and root canals.[16–17]

In orthodontics, FEM has been used successfully to model the application of forces to single-tooth systems. Alveolar bone loss was shown to lower the center of resistance of the tooth and alter the stress patterns on the root.[18–20] Similar changes were observed in altering root length.[21] FEM was also used to show that areas of bone remodeling in vitro corresponded with the same areas in vivo.[22] Canine retraction has been modeled by FEM. The stresses in the periodontal ligament (PDL) were quantified during canine retraction in several studies.[23–25] The center of rotation was determined to be two-fifths of the root length from the CEJ.[26] It has also been shown by FEM that the biomechanical properties of the periodontal ligament are different between adults and adolescents.[27] Recent work focusing on the more complicated rendering of the first molar has shown that stress is concentrated in the furcation, not the apex.[28]

The purpose of this study is to investigate the types of orthodontic forces that cause higher stress, specifically at the root apex of the maxillary central incisor. The maxillary central incisor was chosen because it undergoes the most detailed tooth movement and is at higher risk for root resorption than all other teeth except the maxillary lateral

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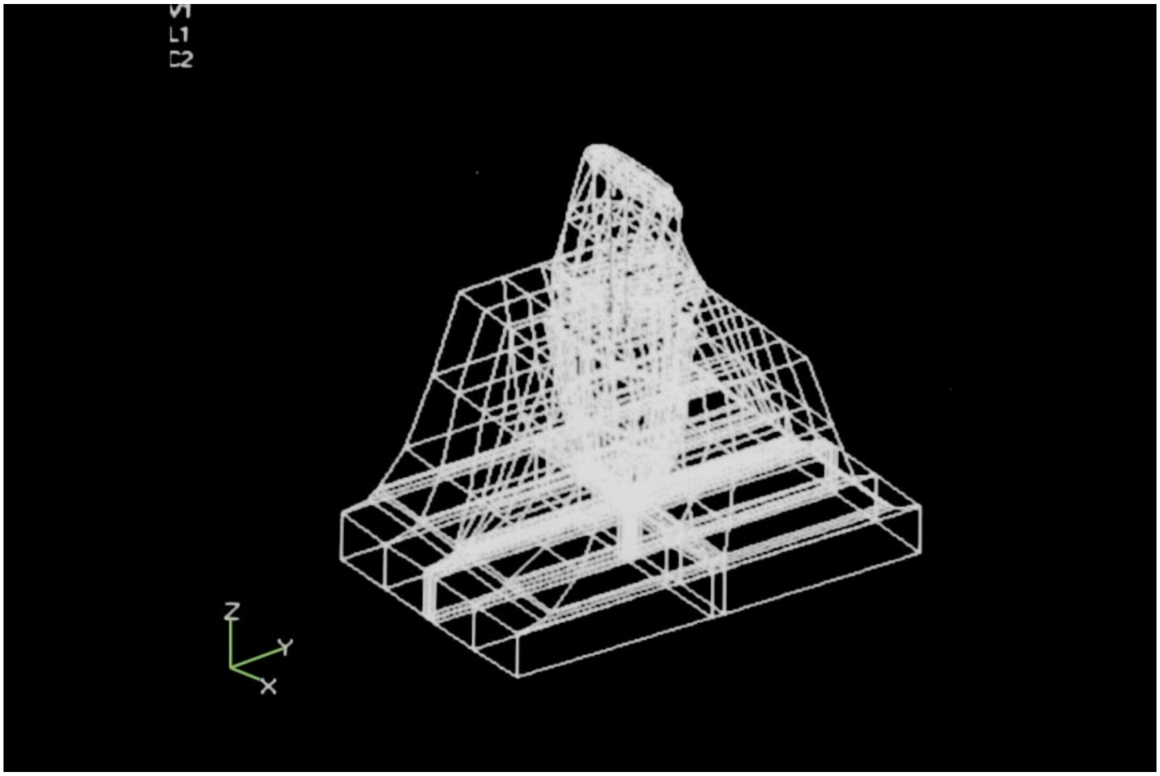

FIGURE 1. Computer-generated 3-dimensional finite element ''meshwork'' of a maxillary central incisor, periodontal ligament, and alveolar bone.

incisor.[29] The majority of previous investigations modeled the maxillary canine or first molar. The model constructed for this study also includes dentin.

MATERIALS AND METHODS

A 3-dimensional finite element of a maxillary central incisor was created, and the stresses from various types of tooth movement were determined. There are 3 primary considerations in the development of the 3-dimensional FEM tooth model: geometry of the teeth and periodontal structures, material properties, and loading configuration.

Model geometry, the geometry of our 3-dimensional finite element model of a maxillary incisor, was created by manually designing the tooth (enamel and dentin), PDL, and bone structure according to the dimensions and morphology found in a standard dental anatomy textbook. The outermost boundary of the tooth was defined 2-dimensionally at first; sectioning the tooth into cross-sections created the third dimension. The model was divided into nonoverlapping wedge- or brick-shaped volumes (elements). Nodes are defined as points at which the corners of these elements meet. The 843 nodes and 644 elements used in this model were manually input into the finite element software that was used for this study (Nastran for Windows software; MacNeal-Schwendler Corp, Costa Mesa, Calif) on a desktop computer (Figure 1). After the model was completed, boundary conditions were defined at all peripheral nodes of the bone with 0° of movement in all directions. Each element was then assigned a specific material property.

TABLE 1. Material Parameters Used in the Finite Element Model

Material	Young's Modulus (N/mm^2)	Poisson's Ratio
Enamel	8.41×10^4	0.33
Dentin	1.83×10^4	0.30
Periodontal ligament	6.90×10^{-1}	0.45
Bone	1.37×10^4	0.30

The material properties of enamel, dentin, PDL, and bone used in this study have been experimentally determined. The material properties used were the average values reported in the literature (Table 1).

The loading configuration was designed to mimic conventional orthodontic tooth movement. Tipping, intrusion, extrusion, bodily movement, and rotation forces were applied at various points of the labial crown surface. Applying 25 g of force perpendicular to the long axis of the tooth simulated tipping. Intrusion and extrusion were modeled by applying 25 g of force directed parallel to the long axis of the tooth. Bodily movement is desired when the torque of the tooth or the tip of the tooth must be maintained, as in closing extraction spaces. Adding the application of a force couple of 2 noncollinear opposing 25-g forces to the tooth model simulated bodily movement. Rotational force was

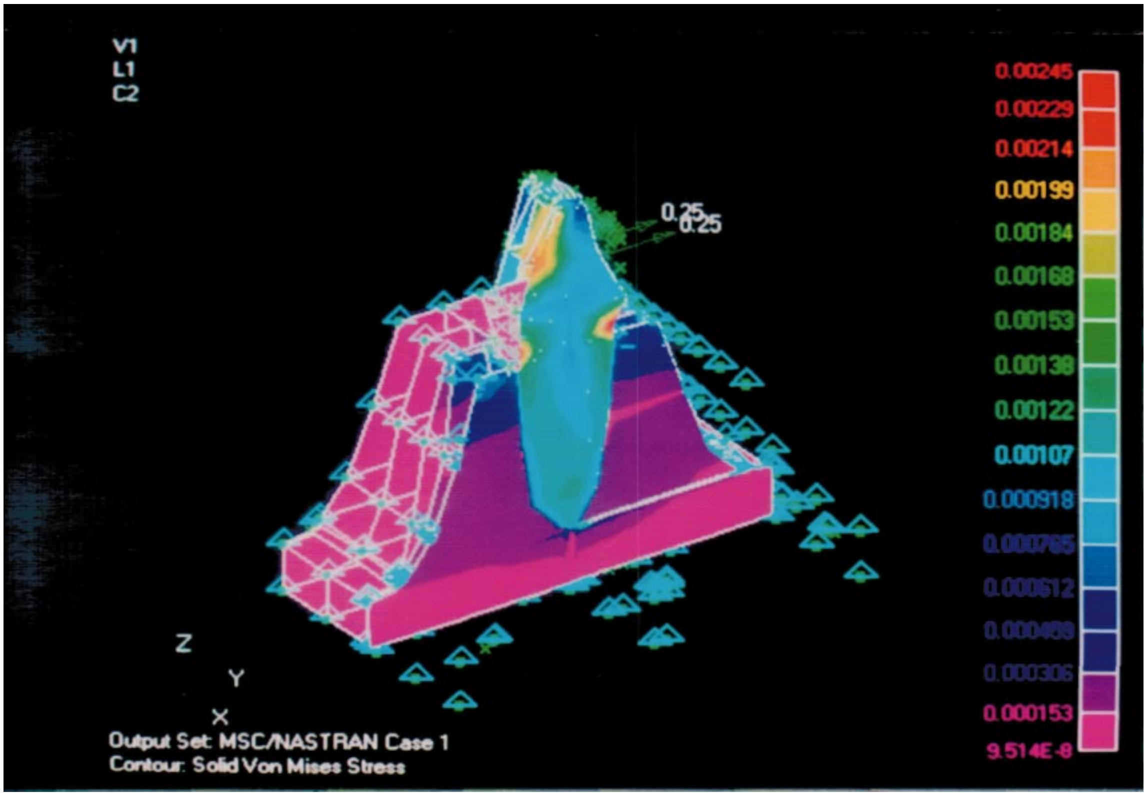

FIGURE 2. Application of 0.25 g of lingual tipping force (arrows). Note red and yellow areas, indicating higher stress where the tooth contacts alveolar crest.

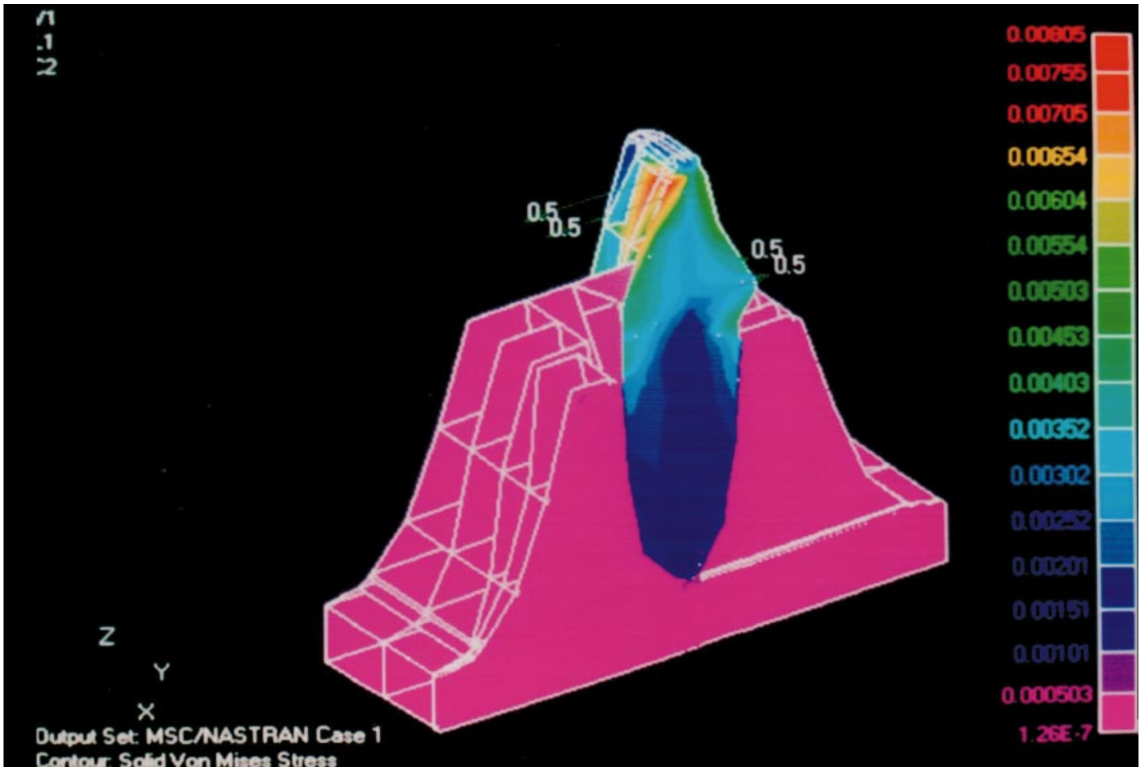

FIGURE 3. Application of 0.5 g of rotational force (arrows). Note general lack of areas of high mechanical stress on the root.

TABLE 2. Stress at Root Apex With Orthodontic Forces

Force Type	Force Magnitude, g	Stress at Apex, N/mm^2
Bodily	25	0.0013
Tipping	50	0.0013
Intrusion	25	0.0017
Extrusion	50	0.0017
Rotation	50	0.0013

created by applying 25 g of force at the line angles of the incisor in opposite directions.

RESULTS

Tipping, extrusion, and intrusion forces resulted in the greatest stress at the root apex (Table 2). As force magnitude increased in these cases, so did the resultant stress in a linear relationship. When bodily movement was simulated in the 3-dimensional FEM model, the stress was distributed throughout the tooth and PDL. Figure 2 shows loading with 25 g of lingually directed tipping force. In this case, the principal stress appeared at the alveolar crest. For intrusion and extrusion, the stress is concentrated mainly at the apex of the root (not shown). Figure 3 shows the stress concentrated at the apex of the root when a 50-g couple of rotational force was placed on the line angles of the incisor.

DISCUSSION

It is clear that different force vectors create different stresses throughout the root. With bodily movement, stress was distributed throughout the length of the tooth, but it was more concentrated at the alveolar crest. This study also showed that most of the force from tipping was concentrated at the crest of the alveolar bone and not at the apex. These results are in agreement with previous studies.[23,24]

Intrusive force resulted in stress mainly at the apex of the root. Interestingly, extrusive forces demonstrated similar stress patterns to that of the intrusive force at the root apex. Similar results were found in previous investigations of vertical tooth movement that used FEM.[30] Rotational forces (defined as the outcome of force application at the line angles of the incisor in opposite directions) produced stress primarily at the apex of the tooth.

As with any theoretical model of a biological system, there are some limitations with FEM. No tooth has the ideal shape and proportion, and linearity assumptions about force distribution in both the hard and soft tissues are problematic. This study and others have, however, demonstrated that the FEM provides a solid, workable foundation for modeling the system. The greatest strength of the FEM model is that it can be magnified nearly infinitely both in terms of the actual volumetric construction itself and the mathematical variability of its material parameters.

What are the clinical implications of this model? If the clinician is concerned about placing heavy stresses on the root apex (for example, a patient whose incisors show previous root resorption) then vertical and rotational forces must be applied with caution. However, the link between external forces and apical root resorption is far from clearcut. Because of the low incidence of severe root resorption and the lack of a reliable animal model, we simply do not know why similar mechanical forces affect one person so differently from another. It is likely that root resorption is a complex, multifactorial system with biochemical thresholds that vary significantly among individuals.[31,32]

CONCLUSIONS

The 3-dimensional FEM model is useful in analyzing the stress that occurs in and around a tooth in response to orthodontic forces. The greatest amount of relative stress at the apex of the maxillary central incisor occurred with intrusion, extrusion, and rotation. Bodily movement and tipping produce forces concentrated at the alveolar crest and not at the root apex. Future studies should compare increasing force levels from lighter (eg, intrusion arch) to heavier (headgear and face masks). Single-tooth models can be improved by adding adjacent and opposing dentition.

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