



An Analysis of the Stress induced in the Periodontal Ligament during Extrusion and Rotation Movements— Part II: A Comparison of Linear vs Nonlinear FEM Study

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ABSTRACT

Background: Optimal orthodontic forces are those which stimulate tooth movement with minimal biological trauma to the tooth, periodontal ligament (PDL) during and alveolar bone. Among various types of tooth movements, extrusion and rotational movements are seen to be associated with the least amount of root resorption and have not been studied in detail. The mechanical behavior of the PDL is known to be nonlinear elastic and thus a nonlinear simulation of the PDL provides precision to the calculated stress values. Therefore in this study, the stress patterns in the PDL were evaluated with extrusion and rotational movements using the nonlinear finite element method (FEM).

Materials and methods: A three-dimensional (3D) FEM model of the maxillary incisors was generated using SOLIDWORKS modelling software. Stresses in the PDL were evaluated with extrusive and rotational movements by a 3D FEM using ANSYS software with nonlinear material properties.

Results: It was observed that with the application of extrusive load, the tensile stresses were seen at the apex whereas the compressive stress was distributed at the cervical margin. With the application of rotational movements, maximum compressive

stress was distributed at the apex and cervical third whereas the tensile stress was distributed on cervical third of the PDL on the lingual surface.

Conclusion: For rotational and extrusion movements, stress values over the periodontal ligament was within the range of optimal stress value as proposed by Lee, with a given force system by Proffit as optimum forces for orthodontic tooth movement using nonlinear properties. During rotation there are stresses concentrated at the apex, hence due to the concentration of the compressive forces at the apex a clinician must avoid placing heavy stresses during tooth movement.

Keywords: Extrusion, FEM, Nonlinear analysis, Optimum force, Rotation.

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INTRODUCTION

Optimal force is the force which results in maximum tooth movement without causing detrimental effects on the periodontium. The stresses generated in the periodontal ligament (PDL) during orthodontic loading is important factor to be evaluated because these stresses transmits to the surrounding alveolar bone resulting in tooth movement.¹ Finite element method (FEM) is one of the best available methods in evaluating the stress pattern and distribution.² Finite element method analysis is of two types linear and nonlinear depending upon the material properties. In realistic situations PDL is anisotropic and is more of nonlinear in nature, by

assigning nonlinear properties to PDL one can get close to the its real behavior.³

In most of the FEM studies, linear models are extensively used but the realistic situations will give rise to nonlinearities.⁴ Hence in this study a comparison of linear and nonlinear study is done. The stress distribution in PDL during extrusion and rotation are rarely studied in the literature, even though these tooth movements are routinely used in the day to day practice. Hence the purpose of this study is to evaluate the magnitude and distribution of stress in the periodontal ligament on application of extrusion and rotation forces on a three-dimensional (3D) FEM model of maxillary central incisor using nonlinear properties.

AIMS AND OBJECTIVES

- To evaluate the distribution of stress pattern in periodontal ligament on application of orthodontic load (viz. extrusive force and rotational force) on maxillary central incisors a 3D finite element analysis (FEA) using linear and nonlinear properties.
- To compare the difference in the magnitude of stress distribution in linear and non linear analysis.

MATERIALS AND METHODS

In this study, a 3D FEM of a maxillary central incisor was created and used to calculate the stress in the periodontal ligament by a 3D FEM and the stresses in the periodontal ligament were analyzed using nonlinear properties.

Computational Facilities used for the Study

Hardware: A PC workstation having an Intel Core DUO processor with 8 GB RAM, 500 GB secondary storage and graphic accelerator were used for the study.

Software: The design program used was SOLIDWORKS release 2012; 3D modeling software and the FEA program used was ANSYS workbench.

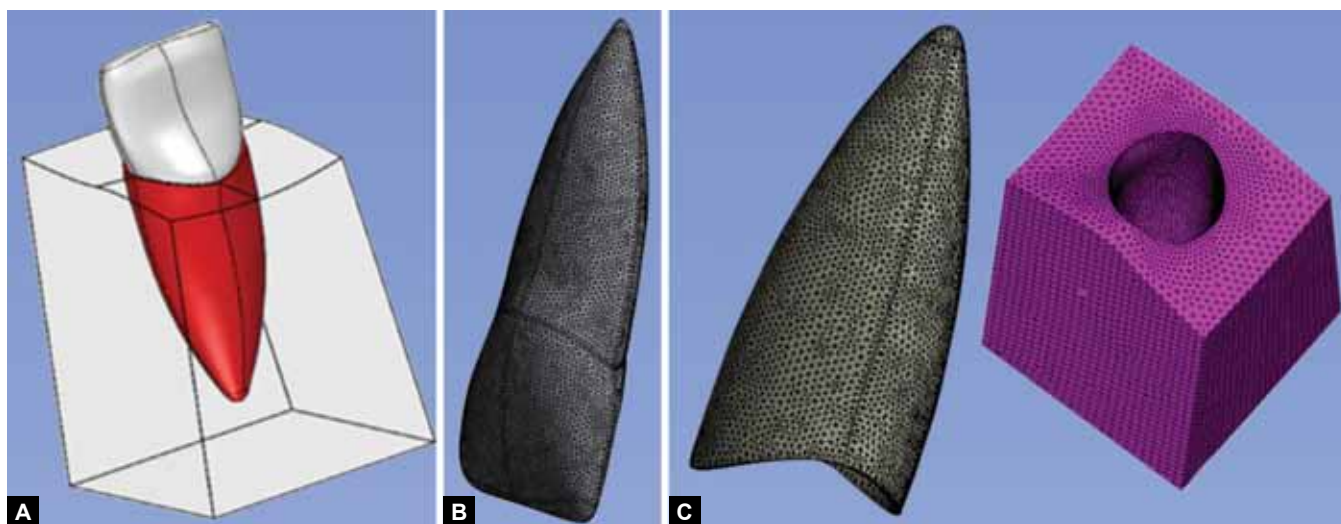
The finite element model consists of geometric model, material properties of the model and loading configuration. In this study the analytical model incorporating maxillary central incisor along with periodontal ligament, cortical and compact bone were developed according to dimensions and morphology found in text book of dental anatomy, physiology and occlusion by Wheeler's.⁵ periodontal ligament was simulated as a 0.2 mm thick membrane around the model of the tooth and cortical bone of 0.5 mm thick⁶ (Fig. 1A). The finite element model approximately consisted of 1,48,097 tetrahedral elements 2,39,666 Nodes and 3° of freedom (Figs 1B and C).

Each structure was then assigned a specific material property. The material properties used in this study have been taken from finite element studies previously conducted.^{7,8} These material properties were defined nonlinear, anisotropic for nonlinear analysis (Table 1).

For extrusion the load was applied parallel to the long axis of tooth away from the apex and for rotation two equal and opposite forces (couple) was applied at the cervical margin of tooth (Table 2).²

RESULTS

The forces were applied on the maxillary central incisor for extrusive and rotational movements and the resulting equations were solved with both linear and nonlinear properties by ANSYS workbench software. The stress patterns produced in PDL were analyzed and calculated in terms of principal stresses. All the minimum principal stresses were considered as compressive stress and were assigned a negative value and all the maximum principal



Figs 1A to C: (A) Geometric model of maxillary central incisor and supporting structures in SOLIDWORKS software, (B) and (C) model showing elements and nodes distribution (1,48,097 elements and 2,39,666 nodes)

Table 1: Nonlinear material properties: Young's modulus: 2.6 (N/mm²), Poisson's ratio: 0.45

Stress	Strain
0.0000	0.0000
0.0251	0.0008
0.0473	0.0021
0.0755	0.0050
0.1009	0.0102
0.1266	0.0197
0.1526	0.0374
0.1789	0.0706
0.1883	0.0882
0.2051	0.1309

Table 2: Loading configuration

Type of tooth movement	Magnitude of force (in Newtons)	Direction
Extrusion	0.35 N	Vertical forces applied along the long axis of the tooth away from the apex
	0.28 N	
Rotation	0.8 N	Two forces of equal magnitude and opposite direction (couple)
	0.4 N	

stresses were considered as tensile stress and were assigned a positive value.

When 0.35 N of extrusive forces were applied along the long axis of the tooth it produced compressive stresses as high as -0.474×10^{-3} N/mm² and the tensile stresses as high as 0.0244 N/mm² in linear analysis. When the same amount of force was applied using nonlinear material properties it produced compressive stresses as high as -0.559×10^{-3} N/mm² and the tensile stresses as high as 0.028 N/mm² (Fig. 2). The stresses were beyond the optimal range as given by Lee¹⁰ (0.015–0.026 N/mm²), hence the force was decreased to 0.28 N through iteration. When 0.28 N of extrusive forces were applied it produced compressive stresses as high as -0.359×10^{-3} N/mm² and

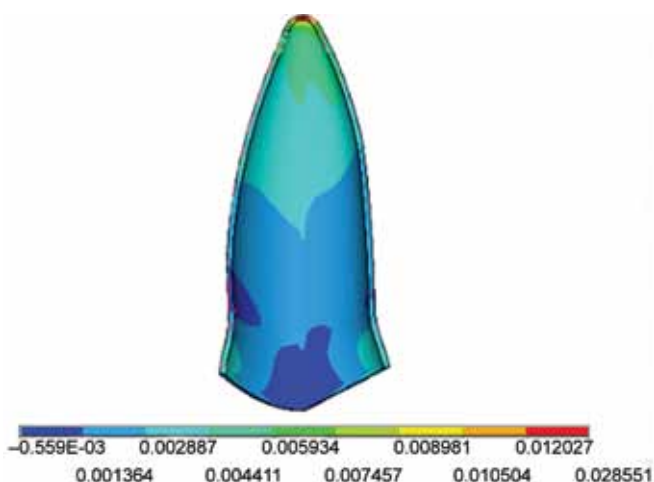


Fig. 2: Distribution of principle stress in PDL on application of extrusive force of 0.35 N using nonlinear properties

the tensile stresses as high as 0.0205 N/mm² which were within the range (Fig. 3).

For rotatory forces (couple) two equal and opposing forces of 0.8 N using linear material properties were applied at the cervical margin of the crown which produced a compressive stress of -0.017 N/mm² and a tensile stress of 0.020 N/mm². With the same amount of couple the nonlinear analysis produced a compressive stress as high as -0.0218 N/mm² and tensile stress of 0.0364 N/mm² (Fig. 4). The stress values were above the optimal range suggested by Lee,⁹ hence through iterations the forces were reduced so that the stress values would fall within the optimal range. With the application of 0.40 N of couple it produced a compressive stress as high as -0.0158 N/mm² and tensile stress of 0.0186 N/mm² (Fig. 5).

DISCUSSION

This study evaluated the magnitude and distribution of stress for extrusion and rotational movements using nonlinear material properties of PDL and it also compared

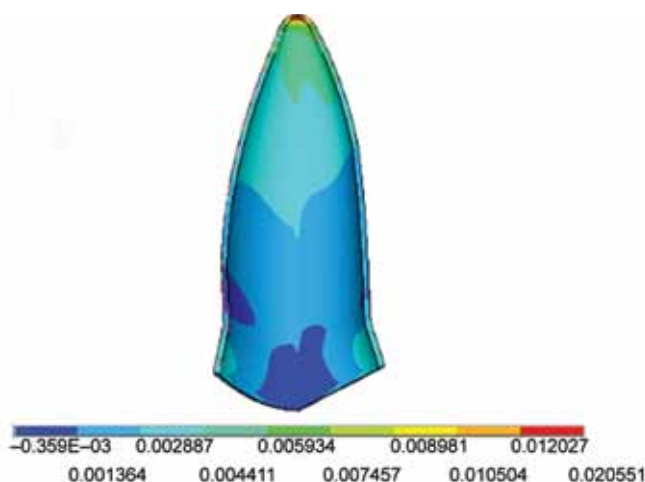


Fig. 3: Distribution of principle stress in PDL on application of extrusive force of 0.28 N using nonlinear properties

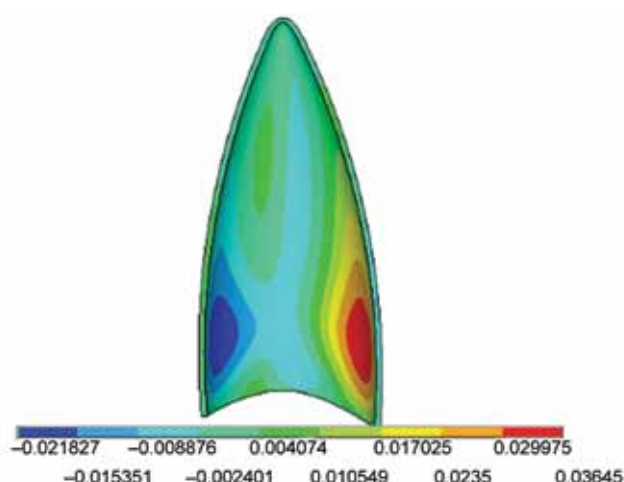


Fig. 4: Distribution of principle stress in PDL on application of rotational force of 0.8 N using nonlinear properties

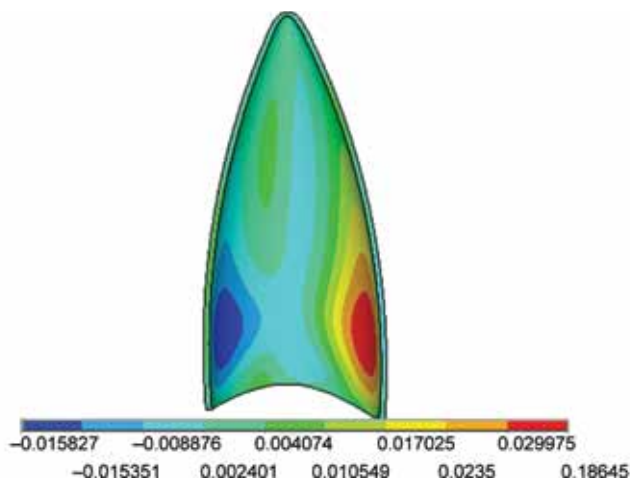


Fig. 5: Distribution of principle stress in PDL on application of rotational force of 0.4 N using nonlinear properties

the difference between linear and nonlinear analysis. The results obtained in the part 1 using linear analysis of this study are also considered. The present study provides a distinctive information about the nonlinear elasticity of the PDL in the range of orthodontic forces for extrusion and rotation. As compared to the linear analysis the nonlinear analysis is known to provide more accurate and reliable results.

With 0.35 N of extrusive force the compressive stress are distributed in the cervical third and in the middle third of the PDL whereas the tensile stress is concentrated at the apex. The similar pattern of stress distribution is seen in a study done by Rudolph et al.² The stress value found with the extrusive force of 0.35N was 0.028 N/mm² which was more than the stresses obtained in linear analysis. With the use of nonlinear mechanical properties for the PDL, it resulted in a dramatic departure from the stresses predicted by the linear models which is in agreement with the study by Toms and Eberhardt.⁴

As the stress values were above the optimal range of stresses proposed by Lee⁹ (0.015–0.026 N/mm²) iterations were done through which the optimal stress values were obtained. At a force of 0.28 N it produced a stress of 0.020 N/mm² which were with in the optimal limits. Interestingly the force value is less than the range of optimal force values as suggested by Proffit¹ (extrusion 35–60 gm).

The pattern of stress distribution for rotational force are that the compressive stress is distributed at the cervical third and apex of the PDL on the labial and lingual surface respectively. The tensile stress is distributed at the cervical third of the PDL on lingual surface. The similar pattern of stress distribution is seen in a study by Rudolph et al.²

With the application of 0.8 N of couple using nonlinear properties the stresses produced were higher than the stress values obtained using linear analysis. This finding is

in agreement with Toms et al⁴ who stated that stress value in nonlinear analysis are higher than linear. However the stress value obtained were 0.0364 N/mm² which was well beyond the optimal stress as given by Lee.¹⁰ Through iterations, the force were reduced till the stress value reached the optimal range and it was found that at the force of 0.4 N it produced a stress of 0.018 N/mm² which was well with in the optimal range.

The magnitude of stress did not coincide with a study done by Kamble et al¹⁰ this could be explained by different material property and force value. Interestingly the force levels are within the optimal range of force value suggested by Proffit¹ (rotation 35–60 gm) unlike in Part 1 of this study in which the force levels were higher than that suggested by Proffit. The stress above –0.03473 N/mm², could cause root resorption as stated by Viwattanatipa.¹¹ In this study, we found that a force of 0.8 N for rotation produced a stress of 0.0364 N/mm², where as the same amount of force in linear analysis produced stresses with in the optimal range. Thus, it can be concluded that nonlinear analysis is a better representation to predict the stress levels in PDL.

CONCLUSION

Stresses in the PDL were evaluated with extrusive and rotational movements by a 3D FEM and these stresses were compared in linear and nonlinear analyses in a maxillary central incisor model. The stresses found in nonlinear analysis are greater than the stresses found in linear analysis for the same force magnitude. Conversely nonlinear analysis requires less force compared with linear analysis. Forces for extrusion is slightly lesser than that suggested by Proffit for the stresses to be with in the optimal range, where as for rotational movements its within in the range.

Since PDL is nonlinear and anisotropic in reality the more accurate response of PDL can be determined by assigning a nonlinear material properties as done in this study. Further the nonlinear finite strain viscoelastic model can simulate both the creeping and nonlinear load displacement behavior which may be the best-fitting model for understanding the mechanical properties of PDL. This property of PDL needs to be addressed in the future studies.

CLINICAL SIGNIFICANCE

With the extrusion and rotational movements as it was found that there is stress concentration at the apex of the tooth. Hence the clinician must be cautious with the forces applied during these tooth movements. The excessive force might cause iatrogenic damage like root resorption or nonvitality.

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