10.5005/jp-journals-10015-1032

RESEARCH ARTICLE

Orthodontic Force Distribution: A Three-dimensional Finite Element Analysis

[1]Hemanth M, [2]Siddharth D Lodaya

[1]Consultant, Department of Orthodontics, Senate and Syndicate Member, Rajiv Gandhi University of Health Sciences, Dayanand Sagar Dental College, Kumaraswamy Layout, Bengaluru, Karnataka, India

[2]Reader, Department of Orthodontics, Dayanand Sagar Dental College, Kumaraswamy Layout, Bengaluru, Karnataka, India

Correspondence: Hemanth M, Consultant, Department of Orthodontics, Senate and Syndicate Member, Rajiv Gandhi University of Health Sciences, Dayanand Sagar Dental College, Kumaraswamy Layout, Bengaluru, Karnataka, India, e-mail: drhemanth@yahoo.com

ABSTRACT

This study was designed to investigate the stress pattern and magnitude in periodontal ligament of maxillary central incisor for tipping and bodily tooth movement using finite element method and to determine the optimal orthodontic force required for bodily tooth movements compared to previous clinical, histologic, and laboratory studies.The three-dimensional FEM consisting of 27000 isoparametric elements of maxillary central incisor was constructed based on the average anatomic morphology given by Wheeler. Principal stresses in PDL were determined for tipping and bodily tooth movement. On application of optimal forces for tipping and bodily tooth movement, stress value seen in PDL was less,however the distribution of stress pattern coincided with the previous studies.

Keywords: FEM, Center of resistance, Tipping movement, Bodily movement, Optimal force.

INTRODUCTION

Force dosage during orthodontic treatment is one of the most challenging aspects in orthodontics. Profit states that tooth movement is primarily a periodontal ligament phenomenon.[1] The quantification of stress in periodontal ligament is important as stress in this tissue is transferred to the alveolus resulting in bone remodelling and subsequent tooth movement.[2]

Storey and Smith stated that an optimum force of 175-300 gm (1.75-3.0 N) was required for bodily canine retraction.[2] Nikolai suggested this to be an erroneous concept and suggested that the force applied to the crown should be equated with the resulting stress in the periodontal ligament.[3]

Lee proposed optimum stress range to be 150-260 gm/cm^2 (0.015-0.026 N/mm^2) was required to produce ideal tooth movement, which was derived by dividing the forces applied to the crown of the tooth by the root surface area.[4]

Various systems[5-8] like conventional mathematical techniques, photoelastic stress analysis, laser holographic interferometric methods have been used to study the reaction of teeth and their supporting tissues to the applied orthodontic force. But all these methods had shortcomings and a major challenge was to study their effect by constructing a three-dimensional model of these tissues with different biomechanical properties.

Finite element method (FEM) is defined as a technique of discrediting a continuum into simple geometric shaped elements, enforcing material properties and governing relationships on these elements, giving due consideration to loading and boundary conditions, which results in a set of equations, solution which gives the approximate behavior of continuum. The finite element is a highly precise technique used to analyze structural stress. FEM is used in dentistry in a wide range of topics, such as structure of tooth, dental implants and root canals.

FEM was developed in 1940 for use in civil and aerospace engineering. This tool was introduced to orthodontics in 1972 by Yettram et al, and since then a number of studies are being carried out by this method.[9] Finite element method is the most suitable means of analysis as it can handle materials of various shapes and nonhomogenous nature.

AIMS AND OBJECTIVES

- To generate the finite element model of the maxillary central incisor and its periodontium.
- To investigate the stress pattern and magnitude of force in the periodontal ligament for tipping and bodily types of tooth movement by means of the finite element method.
- To determine the optimal forces for bodily movement of the central incisor in relation to previous clinical, laboratory and histologic studies.

MATERIALS AND METHODS

FEM has been applied successfully to study stress and strain in the field of engineering and in living structure. Finite element model is the representation of geometry in terms of finite number of elements and their points called Nodes. These are the building blocks of numerical representation of a model (Zienciewicz).[10]

Steps involved in Finite Element Modeling

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. Loading configuration
6. Solving the system of algebraic equation
7. Interpretation of results.

Construction of the Geometric Model

The purpose of geometric modelling is to represent a geometry of points (grids), lines, surfaces (patches) and volume (hyper-patches).

The analytical model of maxillary central incisor was developed according to the dimensions and morphology found in Wheelers' text book.[11] An average PDL thickness was taken as 0.25 mm around the model of the root.

The software used for geometric modeling was pro/engineering (Pro/E).

Conversion of Geometric Model to Finite Element Model

This geometric model was converted to finite element model using ANSYS software. The elemental shape described was a solid 10 noded tetrahedron with 3 degrees of freedom. Each element was connected to adjacent element with the help of nodes. FEM consisted of approximately 27,000 elements and 30,000 nodes (Fig. 1).

Material Property Data Representation

The material property of each tooth structure used in this study was taken from FEM studies conducted by Mc Guinness NJP[12] (Table 1).

In this study, the properties of all tissues were assumed to be same in all directions, i.e. isotropic.

Defining the Boundary Condition

The boundary conditions in FEM was defined at all peripheral nodes of bone with no movement (0 degree) in any direction.

Application of Forces

The loading configuration was designed to simulate conventional orthodontic movement. The magnitude of force applied was same as that used previously by David Rudolph et al[13] and was within the optimal loading range as proposed by Proffit[1] (Table 2).

Solving the System of Linear Algebraic Equations

The sequential application of the above steps leads to a system of simultaneous algebraic equations where the nodal displacements are unknown.

Interpretation of Results

RESULTS

Tipping Force

A 50 gm force directed lingually and perpendicular to the long axis of the tooth produced 0.17152 N/mm^2 compressive stress at the cervical margin on the lingual side and tensile stresses 0.024357 N/mm^2 at the cervical margin on the labial surface (Fig. 2).

Fig. 1: Finite element model of tooth and peridontium

Table 1: Material parameters used in finite element model

Material	Young's modulus (N/mm^2)	Poisson's ratio
Enamel	8.41×10^4	0.33
Dentine	1.83×10^4	0.3
Periodontal ligament	6.90×10^{-1}	0.45
Cancellous bone	1.37×10^4	0.3
Cortical bone	3.45×10^2	0.3
Pulp	1.0×10^{-1}	0.3

Table 2: Force systems applied

Force type	Force magnitude (gm)	Direction
Tipping	50	Horizontal force in a lingual direction applied perpendicular to the long axis of the tooth
Bodily movement	50	Horizontal force in a lingual direction with a couple in a buccal crown direction

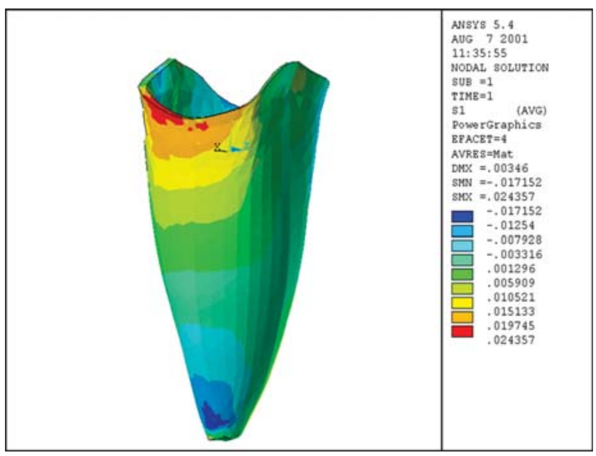

Fig. 2: Stress distribution in periodontal ligament during tipping

Bodily Movement

If two forces are applied simultaneously to the crown of the tooth, the tooth moves bodily.

A 50 gm force and a 430 gm/mm couple applied 13.6 mm from the center of resistance produced 879E-03 N/mm^2 compressive stress in the middle of the PDL on the lingual side and 0.0933 N/mm^2 tensile stress on the labial side (Fig. 3).

As the net force was increased by iteration, at 209.6 gm, compressive stress of –0.01607 N/mm^2 was produced in the middle of PDL on the lingual side and 0.024342 N/mm^2 tensile stress (Fig. 4).

DISCUSSION

This study investigated the magnitude of stress and stress pattern in the PDL for tipping and bodily tooth movement using FEM. The simplest form of orthodontic tooth movement is tipping. Tipping movements are produced when a single force is applied against the crown of the tooth. When this is done only one half of the PDL is loaded (compressed), for this reason forces required to tip a tooth is low.

In this study, stresses produced were within the optimal range as suggested by Lee[4] (0.015-0.26N/mm^2) with the loading configuration as given by Proffit (35-60 gm). The distribution of stress pattern and the values coincide exactly with the previous study done by David Rudolph et al (0.013 N /mm^2) at the tip of the root.[13]

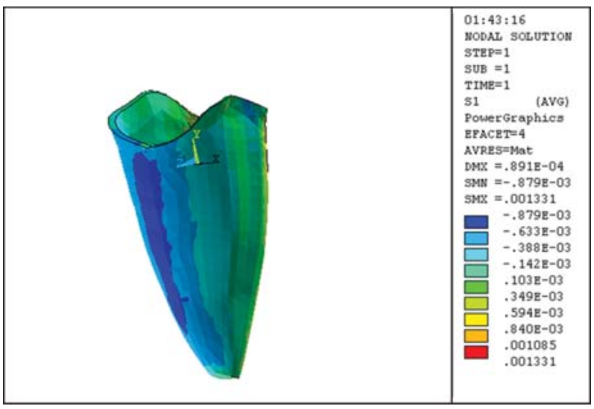

Fig. 3: Stress distribution in periodontal ligament during bodily movement with a net force of 18.4 gm

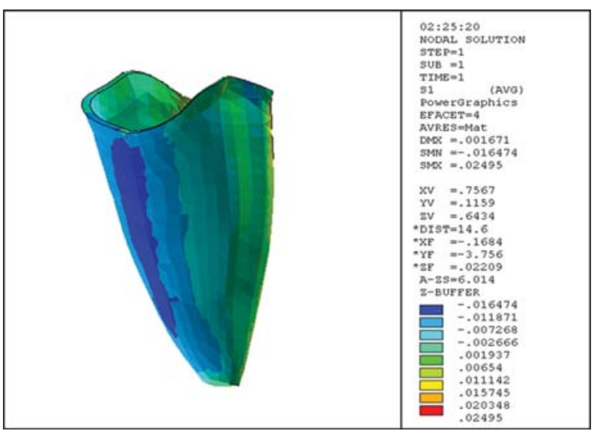

Fig. 4: Stress distribution in periodontal ligament during bodily movement with a net force of 209.6 gm

Tipping Movement

The distribution of stress patterns and the values exactly coincide with the previous by David Rudolph et al (0.013 N/mm^3) at the tip of the root.

When tipping forces were applied to the crown of a canine tooth model Mc Guiness et al, when found stresses at the cervical margin to be 0.132 N/mm^2 for a 1 N tipping force, applied mesiodistally at the center of the crown.[14] A buccopalatal tipping force produced a stress of 0.086 N/mm^2 at the level of cervical margin of the periodontal ligament.

This study showed less stress values and this may be attributed to the type of the tooth and the magnitude of force being different. A force applied in the present study was only 50 gm on a maxillary central incisor.

Bodily Movement

If two forces are applied simultaneously to the crown of a tooth, the tooth can be moved bodily. Therefore, for the same stress response, more force is required for bodily tooth movement as compared to tipping movement.

When a net force of 18.4 gm (50 gm labially and 31.6 gm lingually) was applied to obtain bodily movement, the stress observed at the middle of the periodontal ligament was well below the optimal stress levels observed by iteration at a net force of 209.6 gm measured at the middle of the periodontal ligament.

So, to obtain the same optimal stress levels during bodily tooth movement as compared to tipping movement, approximately 4.19 times more force is required.

The results coincide with the previous study done by Kazuo Tanne et al[15] where they required approximately four times the tipping force for bodily tooth movement.

The results of the present study are not similar to that reported by Proffit[1] where he suggested twice the tipping force (70-120 gm) would be required for bodily tooth movement.

The forces used in the present study are within the range stated by Storey and Smith for bodily canine retraction which was 175-300 gm.

With all these results, it was found that only tipping force value (35-60 gm) by Proffit was optimum force for orthodontic tooth movement. But force values proposed by Proffit were well below the optimal stress values proposed by Lee.[4]

It is difficult to correlate the findings, as each author's method is different from the present study and it might be due to some restraints of this study also.

Further the technology to reproduce the anatomic tooth structure by nonlinear FEM would enrich us to generate ideal stress values.

SUMMARY AND CONCLUSION

It was clear that different force vectors create different stresses throughout the periodontal ligament.

During bodily movement, a net force of 209.6 gm produced a similar optimal stress level as proposed by Lee.

This force of 209.6 gm was found to be 4.19 times the force required to bring about tipping movement.

The question of optimal force magnitude remains an important enigma in orthodontics.

For the results of this study, a first approximation of stress should be evaluated more from relative numbers rather than absolute values. In this way, the results are useful in suggesting the required forces needed for different types of tooth movement.

The periodontal ligament in this instance was considered to be isotropic and elastic. This assumption may be adequate for the purpose of investigating instantaneous tooth movement but may not be so for any investigation involving secondary tooth movement with bone remodeling.

It has been demonstrated that tooth mobility increases in a quasilogarithmic manner with the recovery also showing a logarithmic phase. This suggests a viscoelastic nature of the periodontal ligament. This property of the ligament will need to be validated.

REFERENCES

1. Proffit WR. Contemporary Orthodontics (3rd ed). Mosby Co., St. Louis 2000;296.
2. Storey E, Smith R. Force in Orthodontics and its relation to tooth movement. Australian Journal of Dentistry 1952;56: 11-18.
3. Nikolai RJ. An optimal orthodontic force theory as applied to canine retraction. American Orthodontist 1975;68:290-301.
4. Lee B. Relationship between tooth movement rate and estimated pressure applied. Journal of Dental Research 1965;44:1053.
5. Burstone CJ, Pryputniewiez RJ, Bowley WW. Holographic measurement of tooth mobility in three-dimensions. J Perio Res 1978;13:283-94.
6. Burstone CJ, Sachdeva RCL, Dermaut LR, et al. Location of centers of resistance for anterior teeth during intrusion using the laser reflection technique. Am J Orhod Dentofac Orthop 1986;90:211-20.
7. Haack CD, Weinstein S. Geometry and mechanics as related to tooth movement studies by means of a 2-D model. J Am Dent Assoc 1963;66:157-64.
8. Baeten LR. Canine retraction: A photoelastic study. Am J Orthod 1975;67:11-23.
9. Yettram AL, Wright KWJ, Houston WJB. Centre of rotation of a maxillary central incisor under orthodontic loading. Br J Orthod 1977;4:23-27.
10. Zienciewicz OC. The finite element method (4th ed). Mcgraw Hill: New York 1988.
11. Wheelers. Wheelers dental anatomy, physiology and occlusion (7th ed). Author-Ash 1993.
12. Mc Guinness NJP, Jones ML, Middleton J, et al. A stress analysis of the periodontal ligament under various orthodontic loadings. Eur J Orthod 1991;13:231-42.
13. David J Rudolph, Michael G Willes, Glenn T Sameshima. A finite element model of apical force distribution from orthodontic tooth movement. Angle Orthod 2001;71:127-31.
14. Mc Guinness N, Wilson AN, Jones M, et al. Stresses induced by edgewise appliances in the periodontal ligament. A finite element Study. Angle Orhod 1992;1:15-22.
15. Kazuo Tanne, et al. Three-dimensional finite element analysis for stress in the periodontal tissue by orthodontic forces. Am J Orthod Dentofac Orthop 1987;92:499-505.