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Research Article

OPTIMAL FORCE LEVELS IN DIFFERENT ROOT MORPHOLOGIES ON TRANSLATION - A 3D FINITE ELEMENT STUDY

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A R T I C L E I N F O

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A B S T R A C T

Background and Objective- The objective of this study was to access the stress patterns in the periodontal ligament of a central incisor with different root morphologies on different orthodontic loads, using the linear, non-linear and viscoelastic finite element analysis and to quantify the optimal force levels for roots with different root morphologies. **Materials and Method**- A finite element model of a maxillary central incisor with different root morphologies was taken and 120g of translative forces were applied. The stress patterns and magnitude in the periodontal ligament was observed for linear, non-linear and viscoelastic properties of the PDL and were compared with the optimal stress range (0.012-0.020 MPa). **Results**- It was observed that, the stress patterns produced in the PDLon translative orthodontic forces were similar for linear, nonlinear and viscoelastic properties of the PDL. The magnitude of stress, varied for all three analyses. For 120 grams of translative force it was seen that, the stress produced were least in linear and highest in viscoelastic analyses. The force applied was decreased in increments of 0.1 gms by iteration, to obtain an minimal stress in the periodontal ligament (0.012 Mpa). It was observed that the force levels had to drop down by two fold in viscoelastic analysis in tooth with different root morphologies. **Conclusion**- From the results obtained, it was observed that the force levels required to produce the same amount of stresses in the PDL of a upper incisor, were the least in viscoelastic analysis, followed by non linear and the maximum in linear analysis. The optimal force levels recommended for translation movements in central incisor with normal root morphology is in accordance with the normal values given by Profitt, but optimal force levels varies in tooth with different root morphologies. Considering that the viscoelastic properties depicts a more realistic behaviour of the PDL, the force levels have to be closely monitored when teeth with different root morphologies is encountered.

INTRODUCTION

Orthodontic tooth movement is a complex procedure based on force-induced remodelling of periodontal ligament and alveolar bone. An optimal orthodontic force is one that enables maximum movement of teeth with minimum damage to tooth and supporting structures[1].However, some studies have reported that orthodontic forces are never distributed equally throughout the periodontal ligament (PDL)[2,3]. The optimal force for tooth movement may thus differ for each tooth morphologies, for each individual patient and for different types of tooth movement. Forces beyond optimal threshold can cause pain, increased mobility, pulp devitality, and root resorption.[1-5]

Root resorption commonly affects the maxillary laterals, maxillary centrals as they travel a longer distance.[4].

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Teeth with abnormal root morphologies[7-9] frequently shows external root resorption, compared to normal root morphology because stress is concentrated at a particular region of the root. Root resorption have been investigated ranging from 2-D to 3-D techniques which provide measurements with inherent[11-13] Finite element method is a highly precise technique to analyze structural stress[4] in the roots, PDL, and trabecular bone upon application of different loads[4]. The method can incorporate linear, nonlinear and visco elastic properties to better understand the mechanical behaviour of thePDL.[15]

Till date no biomechanical study has been done that documents the influence of translatory movement on various root morphologies (normal, short, blunt, dilacerated and pipette) during orthodontic force application. Thus, the present study aims to analyse the effects of translation on central incisor with different types root morphologies using FEM model.

MATERIALS AND METHODS

Computational Facilities Used For the Study

Hardware specification

- RAM: 128GB
- Disk Space: 4TB
- PROCESSOR: INTEL®XEON®e5-26090 @2.40GHz

Software specification- Abaqus Explicit 6.14

1. For finite element modelling: The design program used is 3-D modeling software, SOLIDWORKS release 2012.
2. For finite element analysis: For calculating stress in finite element analysis ANSYS workbench R 14.5 version

Steps Involved In the Generation of Finite Element Model

Construction of the geometric model

The analytical model incorporating maxillary central incisor along with periodontal ligament, cortical and compact bone were developed. Data required for the study was obtained from preexisting CBCT scans (high resolution DICOM). [13] Periodontal ligament was simulated as a 0.2mm thick ring around the model of the tooth and cortical bone at 0.5mm thick.[14]

With software SOLIDWORKS surfaces were generated and this data was exported in IGES format to ABAQUS workbench.(Fig 1,2)

Conversion of geometric model to finite element model

This geometric model in IGES format was imported for creating a finite element model consisting of nodes and elements using discretization technique. The basic theme was to make calculations at only limited (finite) number of points and then interpolate the results for the entire domain (surface or volume). Hence in FEM the infinite degree of freedom was reduced to finite with the help of MAC meshing. (Fig 3,4)

Number of nodes: **11,47,343 nodes**
Number if elements: **2,82,372 elements**
Type of elements **: Tetrahedral**
Boundary conditions: **Cortical bone was fixed in all degrees of freedom**

Force applied in X and Y direction on Enamel

Material property date representation

The mesh is programmed to contain the material and structural properties(elastic modulus, Poisson's ration and yield strength)which define how the structure will react to certain loading conditions. The different structures in the finite element model are tooth, periodontal ligament, cortical bone and cancellous bone was then assigned a specific material property.The analysiswas performed as linear, non- linear and viscoelastic analysis depending on the allocation of appropriate physical characteristics to the different parts of the tooth.The material properties used have been taken from finite element studies previously conducted.[16,19](Tables II, III, IV)

Defining the boundary condition

The boundary condition, in the finite element model was defined at all the peripheral nodes of the bone with no degree of movement in all directions. Boundary conditions were assigned to the nodes surrounding the outer most layers of the tooth, roots and alveolar bone.

Table 1 Loading configuration designed to simulate conventional orthodontic tooth

S.No	Type of Loading	Magnitude and direction
1	Translation	70-120 grams of horizontal force in lingual direction with a counter tipping moment

Table II Linear material properties of periodontal ligament in Finite Element Analysis

Part	Density	Young's Modulus	Poisson's ratio
Periodontal ligament	1.5E-09 (TONNES/mm³)	0.69 MPa(LINEAR) 0.032MPa(NON LINEAR)	0.33
Enamel	2.99E-09 (TONNES/mm³)	84100 MPa	0.3
Cortical bone	2.99E-09 (TONNES/mm³)	345 MPa	0.3

Table III Continuous nonlinear material properties of periodontal ligament in Finite Element Analysis

	Yield Stress	Plastic Strain
1	1E-005	0
2	0.0008	0.025
3	0.0008676559083	0.0251
4	0.001617539833	0.046
5	0.00254749844	0.073
6	0.003338719812	0.095
7	0.004172148662	0.119
8	0.004970709101	0.142
9	0.005760363011	0.165
10	0.006038330001	0.173
11	0.006529689287	0.187

Table IV Viscoelastic material properties of periodontal ligamnet in Finite Element Analysis

Viscoelastic
Domain: Time
Time: Frequency data
Type: Isotropic Traction
Preload: None Uniaxial Volumetric Uniaxial and Volumetric
Maximum number of terms in the Prony series: 13
Allowable average root-mean-square error: 0.001
Test Data
Suboptions
Data

	Omega g* real	Omega g* imag	Omega k* real	Omega k* imag	Frequency
1	1.7548039E-005	-1.98034E-010	0	0	1E-005
2	0.00017548038	-1.98034E-008	0	0	0.0001
3	0.0017547991	-1.98032E-006	0	0	0.001

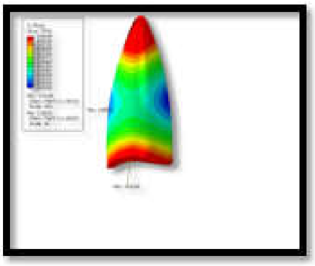
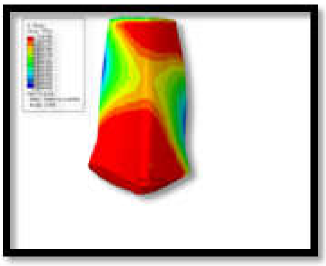
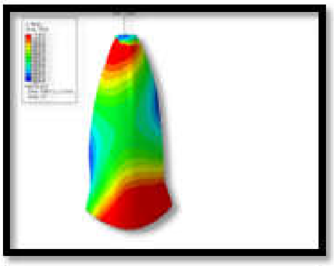
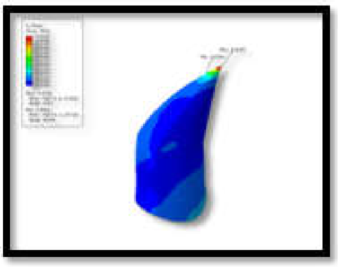
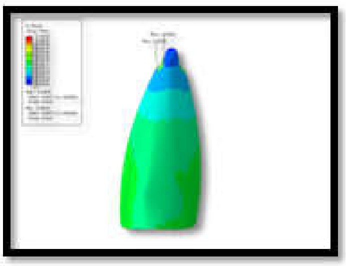
Application of forces

The loading configuration was designed to simulate conventional orthodontic tooth movement. Tipping and translative forces were appliedwithin the range of optimum forces as proposed by Profit. (Fig 5 and table I)

Solving the system of algebraic equations

The sequential application of the above steps leads to a system of simultaneous algebraic equations which had to be solved using linear, non linear and visco elastic properties.

Table V Pattern of Stress Distribution in the PDL

Translation	Stress distribution
	No significant stress concentrations was observed on the root
	Significant stress was concentrated at the neck of the root.
	Stress level at theroot apex wasdecreased
	Stress wasconcentrated at the middle and apical regions of theroot
	Stress was concentrated at the apex of the root

RESULTS

Orthodontic force application on tooth produces areas of compression and tension in the PDL. In this study, the stress levels within the PDL on application of translative orthodontic forces were calculated in terms of Von Mises. The Von Mises stress is used to check if a structure will withstand a particular load and were assigned a positive value.

The patterns of stress distribution were compared between linear, nonlinear and viscoelastic material properties of the periodontal ligament for all the root morphologies (normal, short, blunt, dilacerated and pipette shaped) during translative movements.

120 grams of translative force (maximum force in the range 70-120 grams by Profitt) were applied to the tooth with different root morphologies

Table -Vshows the Patterns of stress distribution in teeth with different root morphologies during translative force.

The following table VI shows the comparison of von mises stress when translation force of 120gms was applied and optimal force for the three analyses in a normal tooth

Normal Root	Force Applied	Stress	Optimal Stress (Lowest value in the range was considered)	Force Required
Linear Properties	120grams	0.015 Mpa	0.012 Mpa	96 grams
Nonlinear Properties	120grams	0.019 Mpa	0.012 Mpa	75 grams
Viscoelastic Properties	120grams	0.025 Mpa	0.012 Mpa	57 grams

The following table VII shows the comparison of von mises stress when translation force of 120gms was applied and optimal force for the three analyses in a short root tooth.

Short Root	Force Applied	Stress	Optimal Stress (Lowest value in the range was considered)	Force Required
Linear properties	120grams	0.018Mpa	0.012 Mpa	80 grams
Nonlinear properties	120grams	0.020 Mpa	0.012 Mpa	72 grams
Viscoelastic properties	120grams	0.026 Mpa	0.012 Mpa	55 grams

The following table VIII shows the comparison of von mises stress when translation force of 120gms was applied and optimal force for the three analyses in a blunt root tooth.

Blunt Root	Force Applied	Stress	Optimal Stress (Lowest value in the range was considered)	Force Required
Linear properties	120grams	0.015 Mpa	0.012 Mpa	96 grams
Nonlinear properties	120grams	0.019 Mpa	0.012 Mpa	76 grams
Viscoelastic properties	120grams	0.028 Mpa	0.012 Mpa	51 grams

The following table IX shows the comparison of von mises stress when translation force of 120gms was applied and optimal force for the three analyses in adilacerated root tooth.

Dilacerated Root	Force Applied	Stress	Optimal Stress (Lowest value in the range was considered)	Force Required
Linear properties	120grams	0.028 Mpa	0.012 Mpa	51 grams
Nonlinear properties	120grams	0.034 Mpa	0.012 Mpa	42 grams
Viscoelastic properties	120grams	0.038 Mpa	0.012 Mpa	38 grams

The following table X shows the comparison of von mises stress when translation force of 120gms was applied and optimal force for the three analyses in a pipette shaped root tooth.

Pipette Shaped Root	Force Applied	Stress	Optimal Stress (Lowest value in the range was considered)	Force Required
Linear properties	120grams	0.014 Mpa	0.012 Mpa	103 grams

Nonlinear properties	120grams	0.022 Mpa	0.012 Mpa	65 grams
Viscoelastic properties	120grams	0.027 Mpa	0.012 Mpa	53 grams

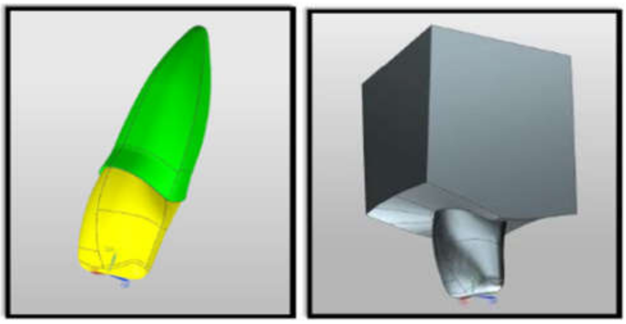


Fig 1 Geometric model showing maxillary incisor, periodontal ligament and the bone

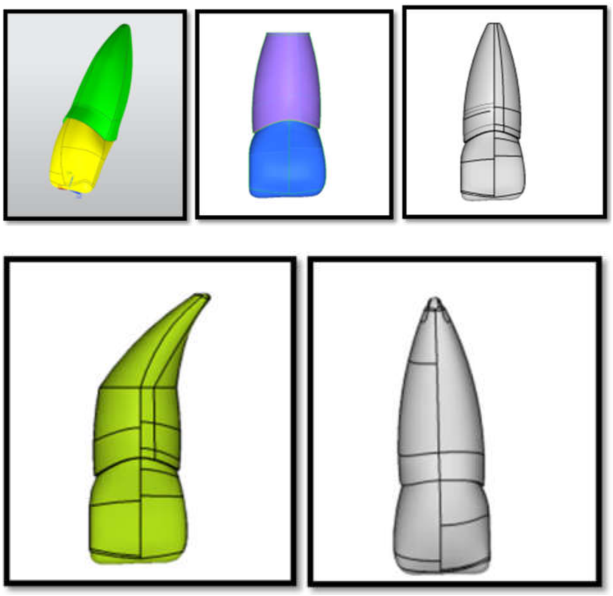


Fig 2 Geometric model showing maxillary incisor with different root morphologies

Fig 3 Finite element Model of the maxillary incisor with its surrounding structures

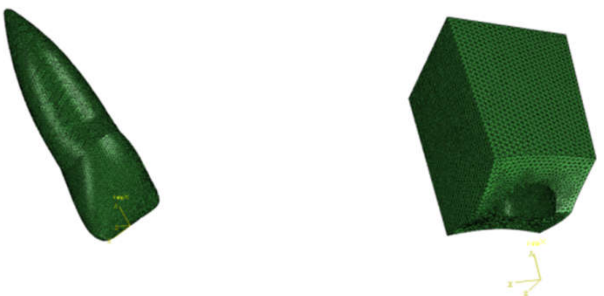


Fig 3a Finite element model of the tooth **Fig. 3b** Finite element model of the tooth

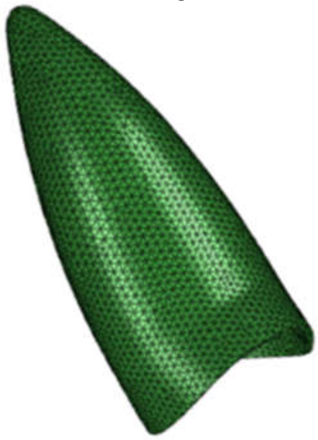


Fig 3c Finite element model of the periodontal ligament

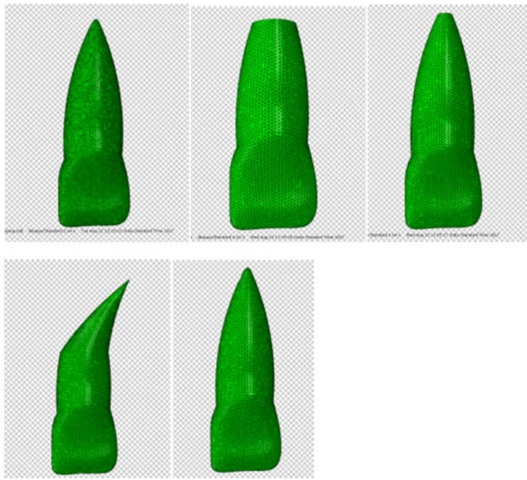


Fig 4 Finite element model of maxillary incisor with different root morphologies

Loading Conditions

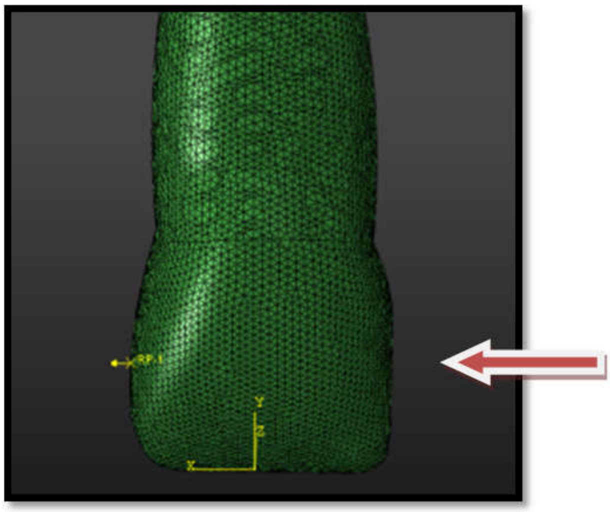


Fig 5 Translation -120 grams of force directed in the horizontal direction, perpendicular to the long axis of the tooth

DISCUSSION

Normal Root Morphology

***Pattern of Stress Distribution in the* PDL**

For model A, (normal root shape) when forces were applied, no significant stress concentration was observed at the root.

Translation

The table VI shows the comparison of von mises stress when translation force of 120gms was applied and optimal force for the three analyses in a normal tooth

In our study, the stresses produced on application of 120 gms of translation forces, were increased in linear non linear and visco elastic analysis.

When the force applied was decreased in increments of 0.1 gms by iteration, it was observed that a force of 96 grams in linear analysis, 75 gms, in non linear analysis and 57 grams in visco elastic analysis was required for the stresses in the PDL to be within the optimal stress range.

Short Root Morphology

Pattern of Stress Distribution in the PDL

In model B (short root), significant stress was concentrated at the neck of the root. This finding is related to the alteration of the crown-root ratio. A decrease in the ratio of the root to the crown is thought to enhance loading on the root, resulting in significant stress. Taithongchai[18] *et al*. David Rudolph [17] *et al*, Kamble[19] *et al*, Koji Oyama[15]*et al* and Thongudomporn and Freer[11] reported that roots with a short apex are at high risk of rootresorption, which supports the findings of the present study.

Translation

The table VII shows the comparison of von mises stress when translation force of 120gms was applied and optimal force for the three analyses in a short root tooth.

In our study, the stresses produced on application of 120 gms of translation forces, were increased in linear non linear and visco elastic analysis.

When the force applied was decreased in increments of 0.1 gms by iteration, it was observed that a force of 80 grams in linear analysis, 72 gms, in non linear analysis and 55 grams in visco elastic analysis was required for the stresses in the PDL to be within the optimal stress range.

Blunt root Morphology

Pattern of stress Distribution in the PDL

Model C (blunt-shaped root) showed no significant stress concentration at the root. The stress level at the root apex was decreased during tipping and translation compared with model A. These findings are partly in accordance with the results of Thongudomporn and Freer[11]David Rudolph [17] *et al*, Kamble[19] *et al*, Koji Oyama[15] *et al*.and Levander and Malmgren. [6]*et al*. In their radiographic studies they reported that blunt-shaped roots frequently showed rootresorption when compared with normal roots. The reason for this difference may be related to genetic or other predispositions. Newman[14]reported that a congenital blunt shaped root results from physical defects and genetic factors during the root formation stage.

Translation

The table VIII shows the comparison of von mises stress when translation force of 120gms was applied and optimal force for the three analyses in a blunt root tooth.

In our study, the stresses produced on application of 120 gms of translation forces, were increased in linear non linear and visco elastic analysis.

When the force applied was decreased in increments of 0.1 gms by iteration, it was observed that a force of 96 grams in linear analysis, 76 gms, in non linear analysis and 51 grams in visco elastic analysis was required for the stresses in the PDL to be within the optimal stress range.

Dilacerated Root Morphology

Pattern of Stress Distribution in the PDL

In model D (dilacerated root apex), stress was concentrated at the middle and apical regions of the root during tipping, and translative force application. The results concerning stress distribution on the dilacerated root shape are in agreement with the findings of Levander and Malmgren[6]*et al*, David Rudolph [17] *et al*, Kamble[19] *et al*, Koji Oyama[15] *et al* and Mirabella and Artun[7] who reported that a bent shape have high chances of root resorption

Translation

The table IX shows the comparison of von mises stress when translation force of 120gms was applied and optimal force for the three analyses in adilacerated root tooth.

In our study, the stresses produced on application of 120 gms of translation forces, were increased in linear non linear and visco elastic analysis.

When the force applied was decreased in increments of 0.1 gms by iteration, it was observed that a force of 51 grams in linear analysis, 42 gms, in non linear analysis and 38 grams in visco elastic analysis was required for the stresses in the PDL to be within the optimal stress range.

Pipette Shaped Root Morphology

Pattern of Stress Distribution in the PDL

For model E (pipette shape), regardless of the direction of force application, stress was concentrated at the apex of the root. In their radiographic studies, Thongudomporn and Freer[11]*et al*, David Rudolph [17] *et al*, Kamble[19] *et al*, Koji Oyama[15] *et al*.and Sameshima and Sinclair[13]described that teeth with a pipette-shaped root apex enhanced root resorption.

Translation

The table X shows the comparison of von mises stress when translation force of 120gms was applied and optimal force for the three analyses in a pipette shaped root tooth.

In our study, the stresses produced on application of 120 gms of translation forces, were increased in linear non linear and visco elastic analysis.

When the force applied was decreased in increments of 0.1 gms by iteration, it was observed that a force of 103 grams in linear analysis, 65 gms , in non linear analysis and 53 grams in visco elastic analysis was required for the stresses in the PDL to be within the optimal stress range.

CONCLUSION

- It was observed that the force levels required to produce the optimal amount of stresses in the PDL of a upper incisor, were the least in viscoelastic analysis, followed by non linear and the maximum in linear analysis.

- Thus, the force levels have to be reduced by almost half in the viscoelastic analysis to produce the same amount of stresses as seen in the linear analysis.
- Considering that the viscoelastic properties depicts a more realistic behaviour of the PDL, the force levels have to be closely monitored when dealing with deviated root morphologies and cautioned not to exceed the recommended optimal value, to prevent iatrogenic damage.
- When tooth with different root morphologies are encountered, optimal force values fortranslativeforces given by profit has to be modified.

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