Mechanical Response to Orthodontic Loading on Posterior Teeth: A Three-Dimensional Finite Element Multitooth Model

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Abstract—**Orthodontic tooth movement is determined by the interaction between applied mechanical forces and the biological response of the periodontal ligament (PDL) and alveolar bone. The magnitude, direction, and point of force application influence stress and strain distribution within the dentoalveolar complex. Finite element analysis (FEA) enables three-dimensional evaluation of these biomechanical responses under controlled loading conditions.[1–3]**

Aim: To evaluate stress and strain distribution in the tooth structure, periodontal ligament, and alveolar bone during initial orthodontic loading of posterior teeth using a three-dimensional finite element multitooth model.

Materials and Methods: **A three-dimensional finite element model of posterior teeth was constructed from computed tomography data. Geometric reconstruction was performed using MIMICS 8.11, finite element meshing using HYPERMESH 2019.1, and numerical analysis using ANSYS 2017.2. A uniform orthodontic force of 0.35 N was applied through a bracket–archwire system. Four loading conditions were evaluated: distal, translational, rotational, and high-anchorage loading with the first molar absent and the second molar serving as the anchorage unit. Equivalent von Mises stress and equivalent elastic strain were evaluated in the tooth structure, PDL, and alveolar bone.**

Results: **Distal loading produced the greatest alveolar bone stress (0.54565 MPa) and bone strain (5.3246×10^{-5} mm/mm). Translational loading produced lower peak stress and a relatively uniform stress distribution, with maximum stresses of 0.1218 MPa, 0.0089854 MPa, and 0.49328 MPa in the tooth, PDL, and bone, respectively. Rotational loading produced the greatest tooth stress (0.22232 MPa) and tooth strain (1.4049×10^{-5} mm/mm). In the high-anchorage condition, tooth stress was lowest (0.088638 MPa), whereas bone stress remained relatively high (0.49648 MPa). PDL strain was consistently greater than tooth and bone strain across all loading conditions.**

Conclusion: **Orthodontic force direction substantially influences stress and strain distribution in posterior teeth and their supporting structures. Distal loading produced the greatest alveolar bone stress, translational loading showed relatively uniform stress distribution, and rotational loading produced the greatest tooth stress. Under increased anchorage demand, mechanical loading was redistributed toward the supporting bone. A three-dimensional multitooth FEA model provides useful biomechanical information for understanding force transmission in posterior orthodontic mechanics.**

Index Terms—**finite element analysis; orthodontic biomechanics; periodontal ligament; posterior teeth; stress distribution; strain; anchorage; tooth movement.**

I. INTRODUCTION

Orthodontic tooth movement is a biologically mediated response to mechanical loading. Application of orthodontic force produces deformation within the periodontal ligament (PDL), followed by cellular and molecular responses that ultimately result in remodeling of the surrounding alveolar bone.[1,4] The mechanical response depends on force magnitude, direction, point of application, tooth morphology, periodontal support, and the material properties of the involved tissues.[5]

Posterior teeth are particularly important in orthodontic biomechanics because they provide anchorage and contribute substantially to occlusal stability. Their larger and anatomically complex roots and surrounding alveolar structures influence the manner in which orthodontic forces are distributed. Consequently, inappropriate force systems may result in unwanted tipping, anchorage loss, excessive periodontal loading, or other biomechanical complications.[5]

Finite element analysis (FEA) has become an important method for investigating orthodontic biomechanics because it permits assessment of stress, strain, and displacement within structures that cannot be directly measured clinically.[2,6] Three-dimensional models further allow evaluation of complex anatomical geometry and force transfer between adjacent teeth. Field et al. demonstrated that multitooth models provide a more clinically representative assessment of orthodontic loading than isolated single-tooth models because forces can be transmitted between neighboring teeth.[7]

Previous FEA studies have demonstrated that different types of tooth movement produce characteristic stress distributions within the PDL and alveolar bone. Tanne et al. reported cervical stress concentration associated with orthodontic loading, while Rudolph et al. demonstrated differences in stress distribution according to the type of tooth movement.[8,9] The PDL also plays a major role in modulating force transmission because of its comparatively compliant and complex mechanical behavior.[10–12]

Despite extensive investigation of individual tooth movement, the biomechanical response of posterior multitooth systems under different force directions and altered anchorage conditions remains clinically relevant. Therefore, the present study evaluated stress and strain distribution in posterior teeth, PDL, and alveolar bone under distal, translational, rotational, and high-anchorage loading using a three-dimensional finite element multitooth model.

II. MATERIALS AND METHODS

Study Design and Model Construction

This in-vitro computational study was conducted using three-dimensional finite element analysis. A posterior dental model was reconstructed from computed tomography data. CT images were converted into a three-dimensional geometric model using MIMICS 8.11 (Materialise, Belgium). The finite element model was subsequently generated using HYPERMESH 2019.1 (Altair, USA) and analyzed using ANSYS 2017.2.

The model incorporated posterior teeth, periodontal ligament, and alveolar bone. Appropriate material properties were assigned to the different structures based on values reported in the literature.[10–12] The model was designed to simulate orthodontic loading through a bracket–archwire system.

Loading Conditions

A standardized orthodontic force of 0.35 N was applied through the bracket–archwire assembly. Four loading configurations were evaluated:

1. Distal force
2. Translational force
3. Rotational force
4. High-anchorage condition (Case 4)—the first molar was absent and the second molar served as the principal anchorage unit.

The forces were applied to the posterior segment under controlled loading conditions. Mechanical responses were evaluated at the initial stage of orthodontic loading.

Outcome Variables

The primary outcomes were:

* Maximum equivalent (von Mises) stress, expressed in MPa.
* Maximum equivalent elastic strain, expressed in mm/mm.

Stress and strain were assessed separately in the tooth structure, PDL, and alveolar bone.

RESULTS

Distal Loading

Distal loading produced the greatest stress concentration in the alveolar bone, particularly around the alveolar crest and cervical region.

The maximum equivalent stresses were:

* Tooth: 0.16472 MPa
* PDL: 0.0091246 MPa
* Bone: 0.54565 MPa

Maximum elastic strains were:

* Tooth: 1.12×10^{-5} mm/mm
* PDL: 1.3267×10^{-4} mm/mm
* Bone: 5.3246×10^{-5} mm/mm

Thus, distal loading produced the highest bone stress and strain among the four loading conditions.

Translational Loading
Translational loading resulted in a comparatively uniform distribution of stress along the root surface, consistent with bodily tooth movement.
Maximum equivalent stresses were:
* Tooth: 0.1218 MPa
* PDL: 0.0089854 MPa
* Bone: 0.49328 MPa
Maximum elastic strains were:
* Tooth: 7.9541×10^{-6} mm/mm
* PDL: 1.3063×10^{-4} mm/mm
* Bone: 4.7858×10^{-5} mm/mm
Compared with distal loading, translational mechanics demonstrated lower peak stress values and smoother stress distribution.

Rotational Loading
Rotational loading produced an asymmetric and circumferential stress pattern consistent with torsional mechanics.
Maximum equivalent stresses were:
* Tooth: 0.22232 MPa
* PDL: 0.0075839 MPa
* Bone: 0.30197 MPa
Maximum elastic strains were:
* Tooth: 1.4049×10^{-5} mm/mm
* PDL: 1.1021×10^{-4} mm/mm
* Bone: 2.348×10^{-5} mm/mm
Rotational loading generated the highest tooth stress and strain among all loading conditions, whereas bone stress was lower than that observed during distal and translational loading.

High-Anchorage Condition
In Case 4, the first molar was absent and the second molar functioned as the anchorage unit.
Maximum equivalent stresses were:
* Tooth: 0.088638 MPa
* PDL: 0.0050007 MPa
* Bone: 0.49648 MPa
Maximum elastic strains were:
* Tooth: 5.2132×10^{-6} mm/mm
* PDL: 8.6226×10^{-5} mm/mm
* Bone: 4.8121×10^{-5} mm/mm
The tooth exhibited the lowest stress and strain of all configurations, whereas the surrounding alveolar bone continued to experience relatively high stress.

Comparative Analysis
Table
Overall, tooth stress followed the order rotational > distal > translational > high anchorage, whereas bone stress followed distal > high anchorage ≈ translational > rotational. PDL strain was greatest during distal loading and remained the highest tissue strain across all configurations.

DISCUSSION
The present study demonstrated that the mechanical response of posterior teeth is strongly dependent on the direction and configuration of the applied orthodontic force. The use of a multitooth model permitted evaluation of force transmission across adjacent posterior teeth and supporting structures, providing a more clinically representative simulation than isolated single-tooth models.[7]

III. DISTAL LOADING

Distal force produced the highest alveolar bone stress (0.54565 MPa), with concentration near the alveolar crest. This finding is consistent with previous FEA studies demonstrating increased stress concentration around the cervical and crestal regions during distalization and other tipping-related movements.[8],[13]
The relatively high bone loading observed with distal force may be related to the directional nature of the applied force and its tendency to produce a moment around the center of resistance. The position of the center of resistance and the point of force application are important determinants of the resulting tooth movement and supporting-tissue response.[14]
The PDL exhibited the greatest strain among the tissues examined. This is consistent with its role as a compliant interface between the tooth and alveolar bone and supports previous finite element investigations demonstrating that inclusion and mechanical representation of the PDL substantially influence stress transmission.[10–12]

IV. TRANSLATIONAL LOADING

Translational loading resulted in a comparatively uniform distribution of stress and lower peak tooth and bone stresses than distal loading. Bodily movement requires a controlled force–moment relationship, and a more evenly distributed mechanical response is expected when the resultant force system acts closer to the center of resistance.[9,14]

The findings are also consistent with previous finite element work demonstrating that different tooth movements produce characteristic stress patterns and that bodily movement can result in a more distributed loading pattern compared with tipping.[9]

V. ROTATIONAL LOADING

Rotational loading produced the highest tooth stress (0.22232 MPa) and tooth strain (1.4049×10^{-5} mm/mm). The circumferential distribution observed in the model reflects the torsional nature of rotational mechanics. Previous investigations have demonstrated that changes in force direction and application point alter the rotational behavior of posterior teeth.[15]

Interestingly, rotational loading produced the lowest bone stress among the three principal force systems. This suggests that, under the loading conditions used in the present model, a greater proportion of the mechanical response was localized within the tooth and PDL rather than being transmitted extensively to the supporting alveolar bone.

VI. HIGH-ANCHORAGE CONDITION

The high-anchorage configuration produced a different pattern. Although tooth stress and strain were lowest, bone stress remained relatively high (0.49648 MPa). The absence of the first molar shifted the anchorage demand to the second molar, altering the pathway of force transmission.

This finding is clinically relevant because posterior anchorage units do not behave independently. Changes in the number and position of anchorage teeth modify the distribution of mechanical loading throughout the dentoalveolar complex. Multitooth FEA models are particularly useful for examining these interactions because adjacent teeth and supporting structures can be incorporated into the same mechanical system.[7]

VII. CLINICAL IMPLICATIONS

The results emphasize that the same magnitude of orthodontic force does not produce the same biomechanical response when its direction or force system is altered. Distal mechanics may produce greater crestal bone loading, while rotational mechanics may concentrate stress within the tooth. Translational mechanics showed relatively balanced load distribution.

The findings also highlight the importance of anchorage planning. When posterior teeth are absent, the remaining anchorage unit may experience altered load transmission. Therefore, force magnitude, direction, point of application, and anchorage configuration should be considered collectively rather than independently.

FEA provides valuable information regarding these mechanical relationships; however, the calculated stress values should not be interpreted as direct biological thresholds. FEA represents a mathematical approximation of a complex biological system and its results depend substantially on model geometry, material properties, boundary conditions, and assumptions.[16]

VIII. LIMITATIONS

Several limitations should be considered. First, the model represents a simplified approximation of the biological environment. The PDL is nonlinear and viscoelastic, whereas computational models frequently use simplified material assumptions.[11,12]

Second, the present analysis evaluated the initial mechanical response and did not simulate the time-dependent biological processes of orthodontic tooth movement, including cellular activity, bone remodeling, and inflammatory responses.

Third, uniform material properties were assigned to the modeled tissues, despite the considerable interindividual variation in bone density, cortical thickness, root morphology, and PDL dimensions.

Fourth, the model was based on a specific anatomical configuration and did not reproduce the complete dental arch, occlusal contacts, muscular forces, or all clinical appliance-related variables.

Finally, the applied force was standardized at 0.35 N and the loading conditions were idealized. Therefore, the findings should be interpreted primarily as biomechanical observations within the modeled conditions rather than direct predictions of clinical tooth movement.

IX. CONCLUSION

Within the limitations of this three-dimensional finite element study, the following conclusions were drawn:

1. Distal loading produced the greatest alveolar bone stress and strain, with prominent loading near the alveolar crest.
2. Translational loading produced a relatively uniform stress distribution and lower peak stresses than distal loading.
3. Rotational loading produced the greatest stress and strain within the tooth structure, reflecting the torsional nature of rotational mechanics.
4. In the high-anchorage condition, tooth stress and strain were lowest, whereas relatively high alveolar bone stress suggested redistribution of mechanical loading toward the supporting bone.
5. The PDL consistently exhibited the greatest strain, supporting its important role in absorbing and transmitting orthodontic forces.
6. A three-dimensional multitooth finite element model provides a useful framework for evaluating force transmission and anchorage behavior in posterior orthodontic mechanics.

Future studies incorporating nonlinear and viscoelastic PDL properties, patient-specific anatomy, complete dental arches, and experimental or clinical validation may improve the clinical applicability of these findings.

REFERENCES

[1] Li Y, Jacox LA, Little SH, Ko CC. Orthodontic tooth movement: the biology and clinical implications. Kaohsiung J Med Sci. 2018;34(4):207–214.

[2] Ko CC, Rocha EP, Larson M. Past, present and future of finite element analysis in dentistry. In: Finite Element Analysis—From Biomedical Applications to Industrial Developments. 2012.

[3] Lahoud P, Faghihian H, Richert R, Jacobs R, EzEldeen M. Finite element models: a road to in-silico modeling in the age of personalized dentistry. J Dent. 2024; 150:105348.

[4] Maltha JC, Krishnan V, Kuijpers-Jagtman AM. Cellular and molecular biology of orthodontic tooth movement. In: Biological Mechanisms of Tooth Movement. 2021. p.33–48.

[5] Nanda RS, Tosun YS. Biomechanics in Orthodontics. Quintessence Publishing; 2019.

[6] Jagota V, Sethi AP, Kumar K. Finite element method: an overview. Walailak J Sci Technol. 2013;10(1):1–8.

[7] Field C, Ichim I, Swain MV, Chan E, Darendeliler MA, Li W, et al. Mechanical responses to orthodontic loading: a 3-dimensional finite element multi-tooth model. Am J Orthod Dentofacial Orthop. 2009;135(2):174–181.

[8] Tanne K, Sakuda M, Burstone CJ. Three-dimensional finite element analysis for stress in the periodontal tissue by orthodontic forces. Am J Orthod Dentofacial Orthop. 1987;92(6):499–505.

[9] Rudolph DJ, Willes PMG, Sameshima GT. A finite element model of apical force distribution from orthodontic tooth movement. Am J Orthod Dentofacial Orthop. 2001;119(5):491–500.

[10] Cattaneo PM, Dalstra M, Melsen B. The finite element method: a tool to study orthodontic tooth movement. Eur J Orthod. 2005;27(6):563–573.

[11] Karimi A, Navidbakhsh M, Razaghi R. Finite element analysis of periodontal ligament under orthodontic loads. J Mech Behav Biomed Mater. 2020; 104:103638.

[12] Huang HL, Hsu JT, Fuh LJ, Tu MG, Ko CC. Biomechanical simulation with different periodontal ligament properties. J Dent Sci. 2020;15(2):200–208.

[13] Asiry MA. Biological and mechanical considerations of orthodontic tooth movement. Saudi Dent J. 2019;31(3):343–349.

[14] Kuruthukulam RM, Patil AS. Center of resistance of a tooth: a review. Biophys Rev. 2023.

[15] Croci CS, Caria PH. Rotation axis of the maxillary molar and maximum tooth movement according to force direction. Braz J Oral Sci. 2015; 14:130–134.

[16] Romanyk DL, Vafaeian B, Addison O, Adeeb S. Finite element analysis in dentistry and orthodontics. Semin Orthod. 2020;26(3):162–173.