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The Finite Element Analysis of Optimal Orthodontic Force for Canine Distalization with Long-Arm Brackets

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Abstract

Objective: To compare the stress distribution in the periodontal ligament under different orthodontic forces during canine distalization using long-arm brackets, and to determine the optimal force value for this device in orthodontic treatment. **Methods:** A finite element model was constructed after extracting the mandibular first premolar, and a long-arm bracket with a traction height of 6 mm was placed on the labial side of the mandibular canine. Three working conditions of 50 g, 100 g, and 150 g were simulated, and the magnitude and distribution of von Mises stress in the periodontal ligament were compared for each condition. **Results:** The maximum von Mises stress in the periodontal ligament was 0.013281 MPa in the 50 g condition, 0.02536 MPa in the 100 g condition, and 0.035549 MPa in the 150 g condition. As the orthodontic force increased, the stress distribution area in the periodontal ligament also expanded. **Conclusion:** A 100 g orthodontic force is the most suitable when using long-arm brackets, providing a relatively uniform stress distribution in the periodontal ligament and keeping the stress within a reasonable range.

Keywords

Orthodontic Force, Tooth Movement, Finite Element Analysis, Periodontal Ligament Stress

1. Introduction

Tooth extraction is a common method in orthodontic treatment, used to close extraction gaps by applying appropriate forces. Optimal force application is essential, as insufficient orthodontic force fails to induce tooth movement, while excessive force may lead to periodontal tissue damage, root resorption, and difficulty in tooth movement [1]-[3]. The use of long arm brackets allows the point of traction to approach the center of resistance of the tooth, facilitating overall tooth movement more effectively. Clinically, the force application point of traditional brackets is located on the crown of the tooth. In order to make the traction point close to the resistance center of the tooth to better achieve the overall movement of the tooth, we weld the long arm on the basis of the traditional bracket to generate a band. Brackets with long arms (long-arm brackets). However, the clinical application of this setup often relies on the practitioner's personal experience, and the optimal orthodontic force value remains unclear. Studying the stress magnitude and distribution in periodontal supporting tissues under varying orthodontic forces is crucial for clinicians to accurately apply appropriate corrective forces.

With advancements in computer technology, three-dimensional finite element analysis (FEA) has become a powerful tool for simulating complex biomechanical environments, allowing precise calculation of stress distribution in teeth and surrounding tissues under various force conditions. This provides significant support in orthodontic biomechanics research [4]-[8]. In this study, we constructed a finite element model following the extraction of the mandibular first premolar and applied a long arm bracket with a 6 mm traction height on the labial side of the mandibular canine. We analyzed the stress magnitude and distribution in the periodontal ligament of the canine under different orthodontic forces to explore the optimal force for distalizing canines using long arm brackets. This research aims to provide scientific guidance for the more rational, scientific, and effective application of orthodontic forces in clinical practice.

2. Methods

2.1. Establishment of the Three-Dimensional Model

A 25-year-old female volunteer with complete and fully developed dentition was selected for this study, exhibiting permanent dentition, normal occlusion, well-aligned teeth, symmetrical dental arches, and no history of orthodontic treatment or maxillofacial trauma. This study was approved by the Ethics Committee of the Affiliated Stomatological Hospital of Guilin Medical University (KQ-0017). She was free of periodontal disease, caries, and tooth loss, with a facial symmetry that was largely consistent bilaterally. Cone beam computed tomography (CBCT) scans of the volunteer's maxilla and mandible in DICOM format were acquired and imported into Mimics 21.0 software (Materialise, Belgium) for initial 3D reconstruction. Thresholding was used to extract the maxillofacial bone and dental tissue based on grayscale differences among tissues. Surface optimization and curve fitting were then performed using Geomagic Design X (Geomagic, USA) to refine the model to accurately represent patient anatomy, followed by storage in STP format. The mandibular bone and teeth were assembled in SolidWorks 2022

(Dassault, France) and saved in PART format. Using Geomagic Design X, a periodontal ligament model was generated by uniformly extending 0.25 mm along the normal direction of the root surface. In SolidWorks 2022, simplified bracket models with and without traction hooks, as well as archwire models (bracket slot size 0.56 × 0.71 mm, archwire size 0.43 mm × 0.64 mm [9], were created. After reconstructing and solidifying the 3D models, they were assembled into a composite structure including the mandible, periodontal ligament, dentition, brackets, and archwire. Finally, the model was imported into ANSYS Workbench 22.0 R1 (ANSYS, USA) for meshing. The final model contained 38 components: one mandible, 12 periodontal ligaments, 12 teeth, two traction hook brackets, ten additional brackets, and one archwire (**Figure 1**).

Figure 1. Three-dimensional finite element overall model for orthodontic biomechanical analysis (mandible including brackets and archwires - periodontal ligament - dentition - brackets - archwires).

2.2. Experimental Condition Setup

A traction hook with a length of 6 mm was established on the gingival side of the canine's labial bracket, with three conditions set using forces of 50 g, 100 g, and 150 g, respectively.

2.2.1. Parameter Definition and Meshing

The model was defined as a continuous, homogeneous, isotropic, linear elastic material. To simplify the model and facilitate finite element analysis, it was assumed that the material properties of the archwire and brackets (including both standard and traction hook brackets) were identical. The elastic modulus and Poisson's ratio of the materials, based on previous studies [5] [10]-[13], are shown in **Table 1**. The model utilized tetrahedral solid elements, with 867,205 meshes and 1,392,788 nodes.

2.2.2. Model Boundary and Calculation Conditions

In order to avoid the movement of the jaw model to simulate the actual clinical situation, the boundary conditions of the model are the peripheral constraints of the bilateral condyles, and the contact between the alveolar bone and periodontal ligament, periodontal ligament and teeth, and teeth and brackets is defined as binding. Contact, the bracket and the archwire are in frictional contact, and the friction coefficient is 0.2 [11].

Table 1. Elastic modulus and Poisson's ratio of materials, physical quantities that describe the elastic properties of materials, and simulate the true deformation behavior of materials when subjected to external forces.

Structure	Elastic modulus (MPa)	Poisson's ratio
Teeth	20700	0.3
alveolar bone	13700	0.3
periodontal ligament	0.68	0.45
arch wire	80,000	0.3
brackets, brackets with traction hook	200,000	0.3

2.2.3. Model Loading and Grouping

Three conditions were set in ANSYS Workbench 2022 R1:

Condition 1: A force of 50 g was applied 6 mm gingivally from the center of the canine bracket base, directed mesially and gingivally toward the buccal tube of the first molar, simulating anchorage from the first permanent molar.

Condition 2: A force of 100 g was applied 6 mm gingivally from the center of the canine bracket base, directed mesially and gingivally toward the buccal tube of the first molar, simulating anchorage from the first permanent molar.

Condition 3: A force of 150 g was applied 6 mm gingivally from the center of the canine bracket base, directed mesially and gingivally toward the buccal tube of the first molar, simulating anchorage from the first permanent molar.

2.2.4. Observational Indicators

Stress distribution and maximum von Mises stress values in the periodontal ligament for each condition were observed.

2.2.5. Calculation and Analysis

Using ANSYS Workbench 2022 R1 finite element analysis software, traction forces were applied to the constructed 3D finite element model. The stress distribution in the periodontal ligament of the anterior and posterior teeth near the extraction site was analyzed and compared across different orthodontic force values.

3. Results

The experimental model was bilaterally symmetrical, and the finite element analysis results were consistent on both sides. To simplify the analysis, the results from the right side of the model were selected for evaluation.

As shown in **Figure 2**, the results for each group indicate that the equivalent stress (Von Mises) distribution cloud map of the periodontal ligament around the canine was similar across conditions, though specific values differed. Red regions indicate areas of maximum stress, while blue regions represent areas of minimum stress. With an increase in orthodontic force, the maximum Von Mises stress in the periodontal ligament of the canine initially decreased and then increased. As depicted in Figure 2, the highest stress in the periodontal ligament consistently appeared on the labial side of the mandibular canine.

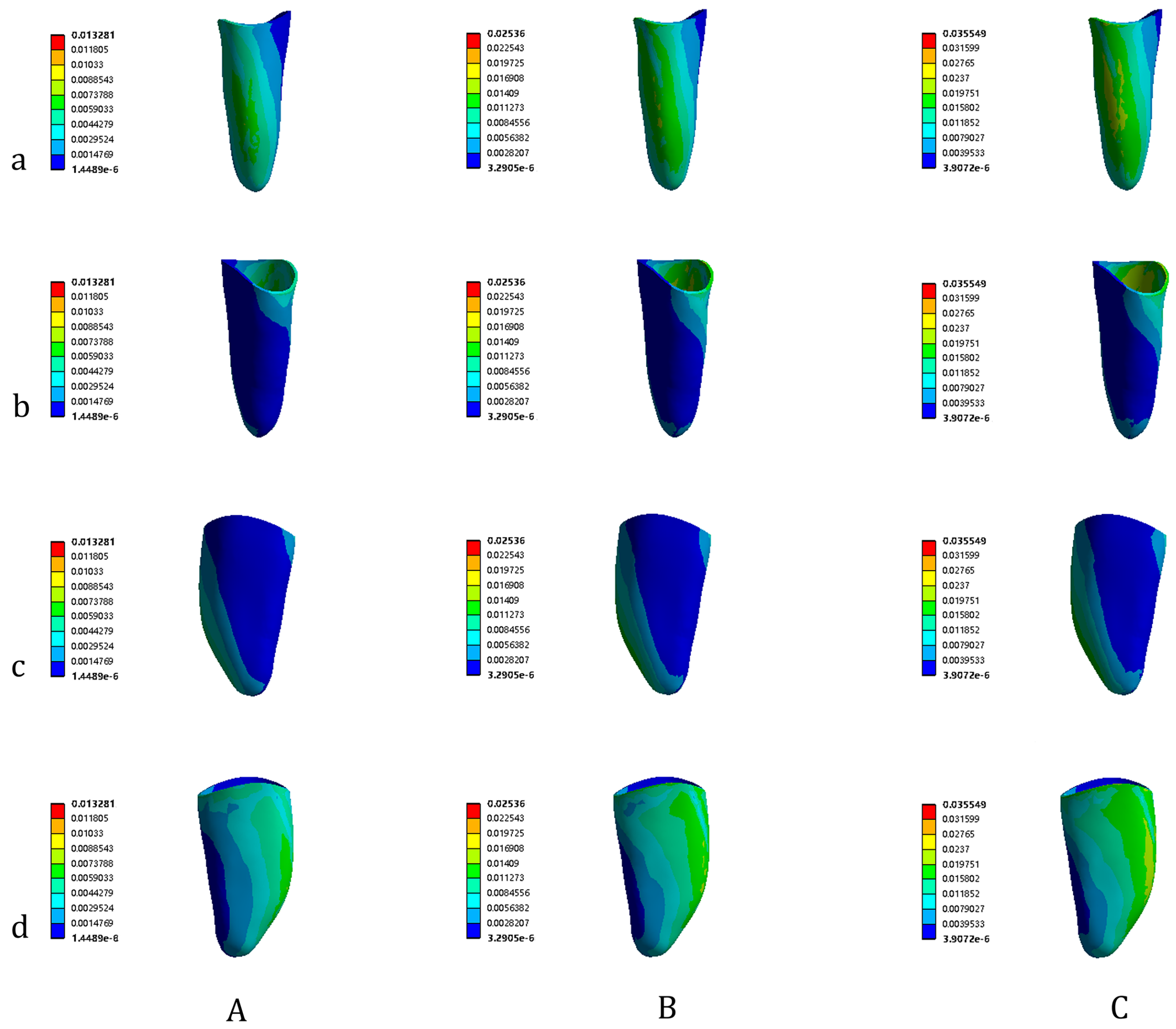

Figure 2. Von-Mises stress distribution cloud diagram of the periodontal ligament of canine teeth under different working conditions. (A): Working condition one; (B): Working condition two; (C): Working condition three. a is the labial side, b is the lingual side, c is the mesial surface, and d is the distal surface. The red area indicates high stress, and the blue area indicates low stress.

At an orthodontic force of 50 g, Von Mises stress in the periodontal ligament was primarily distributed on the labial side of the canine's periodontal ligament, the cervical third of the lingual side toward the distal surface, and slightly on the mesial side near the labial surface, with stress values ranging from 1.4489e−006 to

1.3281e−002 MPa. At 100 g, Von Mises stress was mainly distributed on the labial side, cervical third to half of the lingual side toward the distal surface, and slightly on the mesial side near the labial surface, with stress values ranging from 3.2905e−006 to 2.536e−002 MPa. At 150 g, the stress distribution expanded further, primarily covering the labial side, cervical half of the lingual side toward the distal surface, apical region of the lingual side, and slightly on the mesial side near the labial surface, with stress values ranging from 3.9072e−006 to 3.5549e−002 MPa. As orthodontic force increased, the stress distribution range within the periodontal ligament progressively expanded.

4. Discussion

In cases of protrusion or severe crowding malocclusion, the first premolar is often the preferred extraction site. Following the extraction of the first premolar, distal movement of the canine becomes a critical step in orthodontic treatment. The canine is situated at the curve of the dental arch, a unique position that plays an essential role in the stomatognathic system, impacting occlusal relationships, temporomandibular joint health, and smile aesthetics. Therefore, exploring safe and efficient methods for distalizing the canine holds significant clinical importance.

In this study, a three-dimensional finite element analysis was used to investigate the stress distribution in the periodontal ligament of the mandibular canine under various orthodontic forces. Finite element analysis not only allows for the assessment of stress distribution within teeth, alveolar bone, and appliances but also enables analysis of stress variations within periodontal tissues, offering unique insights into orthodontic biomechanics. These findings provide clinicians with a more reliable basis for developing orthodontic treatment plans.

4.1. Feasibility of the Experiment

This study developed a comprehensive finite element model incorporating the mandibular dentition, alveolar bone, periodontal ligament, brackets, and archwire. Compared to the single-tooth or isolated dental arch models commonly seen in previous studies, this model offers greater geometric similarity and overall integrity, closely mirroring actual clinical scenarios. This allows for a more accurate simulation of biomechanical effects during orthodontic treatment.

Since the model was based on CBCT data from an untreated volunteer, there are some positional discrepancies between the bracket placements in this model and actual clinical applications. Specifically, the volunteer's curve of Spee (The Spee curve is the longitudinal curve of the lower dental arch, connecting the incisal edges of the lower incisors, the cusps of the canines, the buccal cusps of the premolars, and the mesial and distal buccal cusps of the molars. It is a concave upward curve from front to back) was not leveled, meaning that the tooth arrangement did not fully align with Andrews' six keys to normal occlusion. To reduce experimental interference and streamline procedures, we standardized the bracket height across the arch, following established literature, ensuring that the straight archwire exerts no additional forces on the teeth when assembled, thus avoiding bias in the experimental results.

In the finite element study by Zhao *et al.* [14], the traction hook was located on the archwire between the lateral incisors and canines. In this study, the traction hook was located on the moving target canine bracket, which can achieve more precise control.In this experiment, a long-arm bracket was designed on the labial side of the canine, with a 6 mm power arm. This length was chosen based on the height of the mandibular canine's center of resistance, ensuring that the applied force passed through the resistance center to facilitate bodily tooth movement. According to prior studies, the distance from the gingiva to the mucogingival fold in periodontal health ranges from 2.5 to 11.5 mm [15], making the selected power arm length both reasonable and clinically relevant.

4.2. Analysis of Periodontal Ligament Stress and Optimal Orthodontic Force

The appropriate force for tooth movement has been a longstanding focus in orthodontics. The optimal force for orthodontic tooth movement is defined as a force sufficient to induce relatively rapid tooth movement without causing discomfort or secondary tissue damage to the patient. Insufficient force fails to initiate tooth movement, while excessive force may lead to adverse reactions, such as root resorption or hyalinization of the periodontal ligament. According to Nikolai [16], evaluating optimal force should focus on the stress state within the periodontal ligament, which is essential for bone remodeling and effective orthodontic tooth movement, rather than simply the force applied to the crown. Although there has been extensive research on the ideal force for tooth movement, no consensus has been reached.

Clinically, the commonly used force values for moving a single anterior tooth are 50 g, 100 g, and 150 g. Therefore, in this study, in order to explore the optimal force value for the distal movement of mandibular canines under the action of long-arm brackets, three traction forces of 50 g, 100 g, and 150 g were selected and compared their impact on the periodontal ligament stress distribution. As shown in **Table 2**, the results showed that the maximum stress in the canine's periodontal ligament was consistently concentrated in the labial region, with the stress distribution extending distally and lingually as the force increased. At a force of 100 g, stress distribution in the periodontal ligament was relatively uniform, and the stress levels (3.2905e−006 to 2.536e−002 MPa) fell within an appropriate range, aligning with Lee *et al.*'s recommended stress threshold of less than 26 kPa [17]. When the force reached 150 g, a notable stress concentration appeared in the lingual root apex area. This shift in stress distribution suggests that excessive force may increase the risk of root resorption and periodontal tissue damage, highlighting the need for careful force selection in clinical orthodontics.

Both stress and strain within the periodontal ligament significantly impact tooth movement. To minimize root resorption while enhancing tooth movement efficiency, it is essential to account for both periodontal stress and strain.

Additionally, forces under 50 g elicit minimal periodontal response, whereas forces exceeding 200 g may lead to soft tissue damage. Therefore, our findings support 100 g as the optimal orthodontic force value.

Table 2. Stress values of periodontal ligament in three groups of working conditions.

Condition	Von Mises stress value of periodontal ligament (unit: MPa)	
	Maximum	Minimum
Condition 1	1.3281e−002	1.4489e−006
Condition 2	2.536e−002	3.2905e−006
Condition 3	3.5549e−002	3.9072e−006

In summary, this study utilized finite element analysis to assess the effects of different orthodontic forces on periodontal ligament stress distribution in mandibular canines with long-arm brackets. The results indicate that a 100 g force is most suitable. This finding provides a scientific basis for clinical force selection, promoting the safe and effective distalization of canines, minimizing root resorption risks associated with excessive force, and potentially reducing treatment duration caused by insufficient force. This study offers a valuable reference for clinical force selection.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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