

Optimal Loading Conditions for Controlled Movement of Anterior Teeth in Sliding Mechanics

A 3D Finite Element Study

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ABSTRACT

Objective: To determine optimal loading conditions such as height of retraction force on the power arm and its position on the archwire in sliding mechanics.

Materials and Methods: A 3D finite element method (FEM) was used to simulate en masse anterior teeth retraction in sliding mechanics. The degree of labiolingual tipping of the maxillary central incisor was calculated when the retraction force was applied to different heights of a power arm set mesial or distal to the canine.

Results: When the power arm was placed mesial to the canine, at the level of 0 mm (bracket slot level), uncontrolled lingual crown tipping of the incisor was observed and the anterior segment of the archwire was deformed downward. At a power arm height of 5.5 mm, bodily movement was produced and the archwire was less deformed. When the power arm height exceeded 5.5 mm, the anterior segment of the archwire was raised upward and lingual root tipping occurred. When the power arm was placed distal to the canine, lingual crown tipping was observed up to a level of 11.2 mm.

Conclusions: Placement of the power arm of an archwire between the lateral incisor and canine enables orthodontists to maintain better control of the anterior teeth in sliding mechanics. Both the biomechanical principles associated with the tooth's center of resistance and the deformation of the archwire should be taken into consideration for predicting and planning orthodontic tooth movement. (*Angle Orthod.* 2009;79:1102–1107.)

KEY WORDS: Sliding mechanics; Power arm; Anterior teeth retraction; Finite element method; Deformation of archwire

INTRODUCTION

The demand for speedy and efficient orthodontic treatment has been increasing in recent years. To meet this demand, sliding mechanics in combination with implant anchorage has become more and more popular throughout the world.^{1–6}

However, the optimal loading conditions for achieving the desired type of tooth movement during space closure in sliding mechanics is still unknown. Control of anterior tooth movement is essential for the orthodontist to execute an individualized treatment plan. The use of power arms attached to the archwire enables one to readily achieve controlled movement of the anterior teeth. That is, the force system for the desired type of tooth movement such as lingual crown tipping, lingual root tipping, or bodily movement can be easily carried out by attaching various heights of power arm to the archwire in sliding mechanics.^{7–10}

Studies of various biomechanical factors affecting tooth movement in sliding mechanics such as flexural rigidity of the archwire, friction, and height of retraction

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Accepted: January 2009. Submitted: November 2008.

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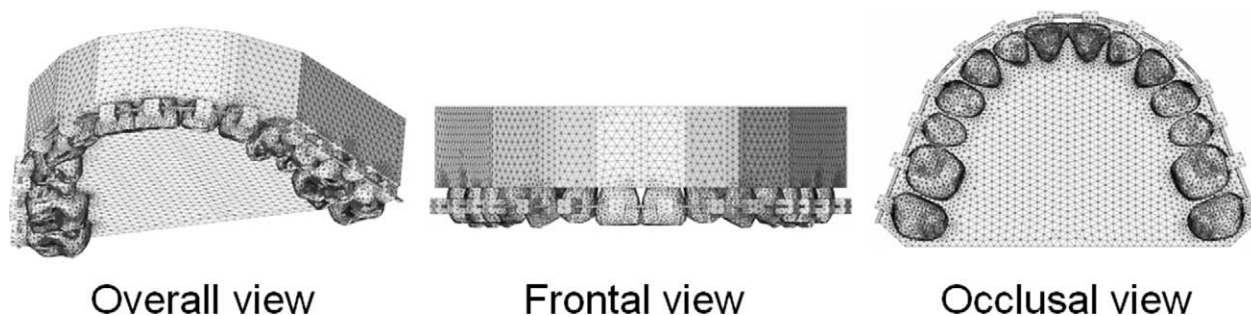


Figure 1. 3D finite element model of maxillary dentition, including PDL, alveolar bone, brackets, and archwire.

force have been reported.⁸⁻¹² Nevertheless, optimal loading conditions for controlled movement of anterior teeth in sliding mechanics by using power arms is still not fully understood. With respect to the finite element method (FEM) study, although single canine retraction has been simulated,^{13,14} no study involving en masse retraction has been reported.

The purpose of this study was to determine the optimal height of power arm retraction force and attachment position on an archwire in sliding mechanics by means of three-dimensional (3D) FEM. Clinical application of sliding mechanics combined with power arms for efficient anterior teeth retraction will also be discussed.

MATERIALS AND METHODS

Three-dimensional Finite Element Model

Using a multi-image micro-CT scanner (3DX, J. Morita, Kyoto, Japan), computed tomography (CT) images of the 14 maxillary teeth were taken. The CT images were saved as DICOM (digital imaging and communication in medicine) data and exported to 3D image processing and editing software (Mimics 10.02, Materialize Software, Leuven, Belgium). The 3D solid model was created and converted to 3D finite element model (FEM) by using finite element analysis pre- and postprocessor software (Patran 2008r1, MSC Software Corp, Los Angeles, CA, USA). Each 3D FEM for periodontal ligament (PDL), alveolar bone, bracket, archwire, and power arm was separately constructed using the same software. Thickness of the PDL was determined to be a uniform 0.2 mm.¹⁵⁻¹⁷ An appliance with 0.018-in bracket slots and an 0.018 × 0.025-in stainless steel archwire was generated. All brackets were sited on the facial-axis points.¹⁸ Four power arms were attached to the archwire at sites mesial and distal to the canine bilaterally and perpendicular to the archwire. Based on these 3D solid models, a finite-element mesh was created to make a node-to-node connection between tooth, PDL, and alveolar bone. A finite element mesh of the archwire was created separately

from the bracket to allow the archwire to slide through the bracket slot. The 3D FEM consisted of 399,320 ten-noded, isoparametric tetrahedral solid elements and 77,612 nodes (Figure 1).

Material Parameters

The material parameters used in this study are represented in Table 1.^{16,17} In order to simplify the model and to reduce the time for analysis, the same properties were given to the archwire, power arm, and bracket. The structures of tooth, alveolar bone, and PDL were modeled as being homogenous and isotropic for the same reason.

Experimental Conditions

Assuming that two titanium miniscrew or miniplate implants, used as skeletal anchorage, were inserted at both sides of the buccal region of the posterior teeth, the retraction force was applied from the implant anchorage to each power arm (Figure 2). The model was a bilateral maxillary first-premolar-extraction case that included 12 teeth. A retraction force of 150 g was applied bilaterally to the power arms parallel to the archwire. The height levels on the power arms were 0, 2, 4, 6, 8, 10, and 12 mm from the bracket slot (Figure 3). The model was restrained in 6 degrees of freedom at the bottom of the alveolar bone to avoid sliding movement of the entire model. Coefficient of friction between bracket slots and archwire was assumed to be 0.2.¹⁹⁻²¹ Under these conditions, 3D finite element analysis was performed by using a 3D finite element

Table 1. Material Parameters of Tooth, PDL, Alveolar Bone, Archwire, Power Arm, and Bracket^a

Material	Young's Modulus (MPa)	Poisson's Ratio
Tooth	20,000	0.30
PDL	0.05	0.30
Alveolar bone	2,000	0.30
Archwire/power arm/bracket	200,000	0.30

^a PDL indicates periodontal ligament.

program (Marc, MSC). We investigated how the archwire is deformed and, consequently, how the maxillary central incisor will move.

RESULTS

The relationship between the degree of labiolingual tipping of the maxillary central incisor and height of the retraction force on the power arm or length of the power arm is shown in Figure 3.

When the power arm was placed mesial to the canine, lingual crown tipping of the maxillary central incisor was observed when the retraction force was at 0 mm (bracket slot level). As the height of the retraction force on the power arm was raised apically from the bracket slot level, the direction of tooth rotation changed from lingual crown tipping to lingual root tipping. At a level of 5.5 mm, no rotation was produced and bodily movement occurred. Lingual root tipping was observed when the retraction force was above 5.5 mm.

When the power arm was placed distal to the canine, lingual crown tipping was produced up to a level of 10 mm. The direction of tooth rotation changed from lingual crown tipping to lingual root tipping between levels of 10 mm and 12 mm. At the level of approximately 11.2 mm, bodily movement occurred. Thus the results showed a large difference in the height level of the power arm where bodily movement of the incisor would be produced.

Figure 4 shows the tooth displacement and deformation of the archwire after the retraction force was applied to the power arm placed mesial or distal to the canine, respectively. For a better understanding of the displacement of the tooth and deformation of the archwire, these movements were magnified 50 times. The initial position of the central incisor is indicated by a dotted line.

When the power arm was placed mesial to the canine at a level of 0 mm, applying the force at bracket slot level caused uncontrolled lingual crown tipping of the incisor, and the apex moved in a direction opposite the retraction force. The anterior segment of the archwire was deformed downward (Figure 4A). Controlled lingual crown tipping, in which the incisor tips around its apex was shown at levels between 4 mm and 5 mm from the finite element analysis. At 5.5 mm, bodily movement of the incisor was produced and the archwire was less deformed (Figure 4B). At 10 mm, the anterior segment of the archwire was raised upward, resulting in lingual root tipping and movement of the apex in the retracted direction (Figure 4C).

When the power arm was placed distal to the canine, uncontrolled lingual crown tipping was observed at 0 mm and the anterior segment of the archwire was

deformed downward as in the case wherein the power arm was mesial to the canine (Figure 4D). Unlike the case of attaching the power arm mesial to the canine, bodily movement did not occur, but uncontrolled lingual crown tipping was produced at 5.5 mm (Figure 4E). The incisors still showed uncontrolled lingual crown tipping at the 10-mm level, and the anterior segment of the archwire was less deformed than when the power arm was located mesial to canine (Figure 4F).

DISCUSSION

In this study, it was found that a close relationship existed between the degree of labiolingual tipping of the maxillary central incisor and the height of the retraction force on the power arm or length of power arm. When the power arm was attached to the archwire mesial to the canine, the retraction force on the power arm below the 5.5 mm level produced lingual crown tipping of the central incisor. Bodily movement was achieved by attaching a power arm 5.5 mm long. Above 5.5 mm, lingual root tipping was observed. In other words, the direction of tooth rotation changed from lingual crown tipping to lingual root tipping as the retraction force height on the power arm was raised from the bracket position toward the apex. On the other hand, when the power arm was attached distal to the canine, lingual crown tipping occurred up to a level of 11.2 mm.

At a power arm height of 10 mm, there were remarkable differences in archwire deformation and resultant incisor movement between attaching the power arms mesial vs distal to the canine (Figure 4C,F). When the power arm was located mesial to the canine, the central incisor showed a relatively great degree of lingual root tipping (Figure 4C). In contrast, when the power arm was attached distal to the canine, lingual crown tipping of the incisor was observed, although the amount of tipping was slight (Figure 4F). As shown in Figure 4C, the anterior segment of the archwire was raised upward due to a bending moment produced between the lateral incisor and canine as a cantilever effect of the power arm mesial to the canine. Consequently, an intrusive force was delivered to the incisors, thereby causing a relatively substantial degree of lingual root tipping. On the other hand, when the power arm was set distal to the canine, the anterior segment of the archwire was less deformed than when the power arm was set mesial (Figure 4F). In fact, the canine is subjected to an intrusive force and the apex is depressed into its socket. However, the adjacent alveolar bone might strongly resist the intrusive action, thus absorbing the force and bending moment generated by the archwire deformation. Therefore, an in-

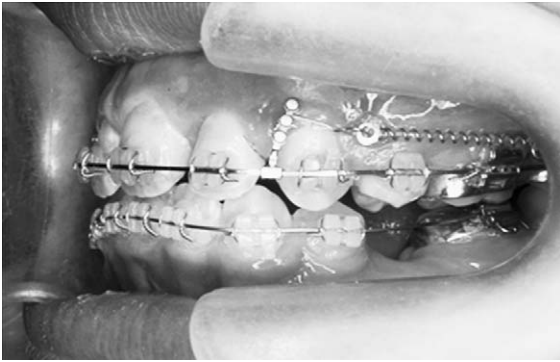
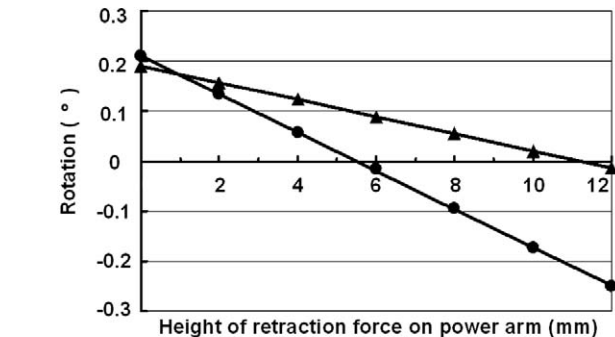
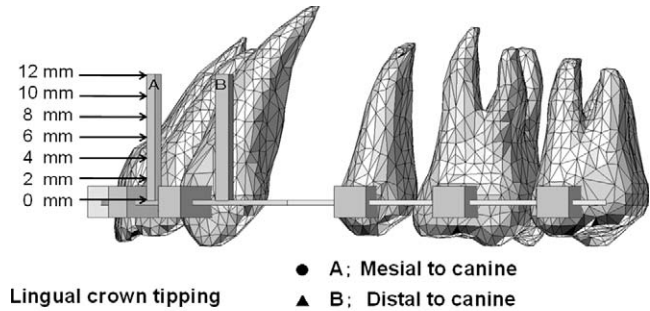


Figure 2. Intraoral picture illustrating retraction of the anterior segment using power arms in sliding mechanics.

trusive force caused by archwire deformation is less likely to be transmitted to the central incisor than when the power arm set mesial to canine. As a result, lingual crown tipping occurred even with a higher level of retraction force, thus demonstrating that the location of the power arm can substantially affect anterior tooth movement.

From the biomechanical standpoint, the relationship between the line of action of a force and the location of the center of resistance of a tooth determines the type of tooth movement that occurs, such as lingual crown tipping, lingual root tipping, or bodily movement.^{7,22,23} However, tooth movements analyzed in this study were not in agreement with those based on this biomechanical principle. That is, there were discrepancies in the loading conditions producing bodily movement between the cases in which the power arms were set mesial and distal to the canine. Theoretically, a single force passing through the center of resistance results in bodily tooth movement. From the present finite element analysis, the location of the center of resistance of the incisor was determined to be 7.5 mm apical to the bracket slot. In other words, bodily movement should occur when the power arm height is at 7.5 mm. However, our results indicated that a power arm height of 5.5 mm allows bodily movement when the arms are mesial to the canine, and 11.2 mm when distal. We thus concluded that the length of the power arm set mesial to the canine should be shorter—and the arm distal to the canine much longer—than the theoretical estimate to achieve certain types of tooth movement.

Knowledge of the biomechanical principles of tooth movement cannot be directly applied in clinical situations in which sliding mechanics are employed. One of the keys to predicting how a tooth will move is an appreciation of the relationship between the line of action of the retraction force and the center of resistance of the tooth. Nevertheless, the effect of archwire deflection of a force system acting on a tooth should also



Lingual root tipping

Figure 3. Degree of tooth rotation as a function of height of retraction force on power arm. Power arm is mesial (A) or distal (B) to canine. Positive signs indicate lingual crown tipping; negative signs indicate lingual root tipping.

be taken into consideration. In sliding mechanics, the height of the retraction force on the power arm affects the type of anterior tooth movement, so that the force system for a desired type of movement (lingual crown tipping, lingual root tipping, or bodily movement) can be designed by attaching various lengths of power arms onto an archwire. Attaching the power arm mesial to the canine would be recommended for better control of anterior tooth movement. The use of a power arm could easily be incorporated into programmed tooth movement, thereby contributing substantially to efficient tooth movement and shorten the sliding mechanics phase of orthodontic treatment. Moreover, combining implant anchorage would further improve the efficiency of orthodontic treatment.

Clinical Application

As previously mentioned, the use of a power arm mesial to the canine enables orthodontists to achieve better control of the anterior teeth in sliding mechanics. In the treatment of Angle Class II division 1 malocclusion, controlled lingual crown tipping, in which the incisor tips around its apex as the center of rotation, is required. In this case, the use of a power arm height of 4 mm to 5 mm is recommended. For Class II division 2, lingual root tipping of the incisor is desirable, which could be carried out by raising the height of the

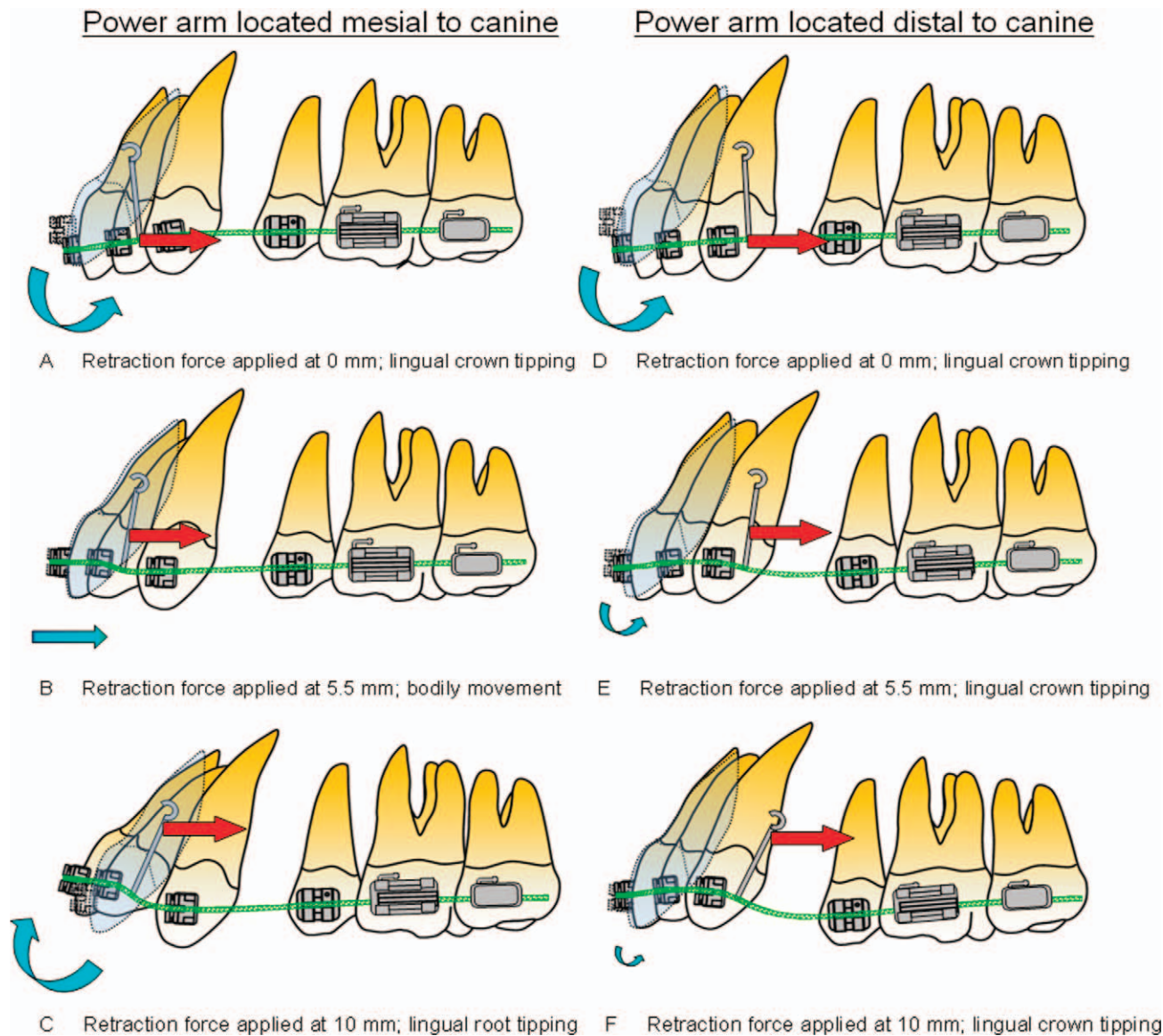


Figure 4. Displacement of maxillary central incisor and archwire deformation after the retraction force was applied to the power arm mesial (left) and distal (right) to canine.

power arm above 5.5 mm. To achieve bodily anterior tooth movement, we propose using a power arm of 5.5 mm, based on the present study.

Several variables affecting biomechanical behavior of tooth movement were not taken into consideration in this study. Further investigation using FEM, including factors involving wire size, bracket slot size, play between bracket slot and archwire, and variable anatomic parameters is still needed.

CONCLUSIONS

- The placement of a power arm between the lateral incisor and canine enables orthodontists to gain better control of the anterior teeth in sliding mechanics.
- In the treatment of Angle Class II division 1 maloc-

clusions, the use of a power arm height of 4 mm to 5 mm is recommended to obtain controlled lingual crown tipping of the maxillary central incisor. For the correction of Class II division 2, the required lingual root tipping of the incisor is carried out by raising the height of the power arm above 5.5 mm. To achieve bodily anterior tooth movement, the recommended length of the power arm is 5.5 mm.

- Considering not only the relationship between the line of action of a retraction force and the location of the center of resistance of a tooth, but also the effect of archwire deformation on tooth movement, may be a great help in establishing an optimal treatment plan and thereby shortening the treatment period.

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