

Numerical simulations of canine retraction with T-loop springs based on the updated moment-to-force ratio

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SUMMARY The purpose of this study was to develop a new finite element method for simulating long-term tooth movements and to compare the movement process occurring in canine retraction using a T-loop spring having large bends and with that having small bends.

Orthodontic tooth movement was assumed to occur in the same manner as the initial tooth movement, which was controlled by the moment-to-force (M/F) ratios acting on the tooth. The M/F ratios were calculated as the reaction forces from the spring ends. For these M/F ratios, the teeth were moved based on the initial tooth movements, which were calculated by using the bilinear elastic model of the periodontal ligament. Repeating these calculations, the teeth were moved step by step while updating the M/F ratio.

In the spring with large bends, the canine at first moved bodily, followed by root distal tipping. The bodily movement was quickly achieved, but over a short distance. In the spring with small bends, the canine at first rotated and root mesial tipping occurred, subsequently the canine uprighted and the rotation decreased. After a long time elapsed, the canine moved bodily over a long distance.

It was found that the long-term tooth movement produced by the T-loop springs could be simulated by the method proposed in this study. The force system acting on the teeth and the movement type remarkably changed during the long-term tooth movement. The spring with large bends could move the canine bodily faster than that with small bends.

Introduction

Prediction of tooth movement produced by an orthodontic appliance will be helpful for clinical treatment planning. The initial tooth movement, which is produced by the elastic deformation of the periodontal ligament (PDL), has been utilized to predict the orthodontic tooth movement. When a moment (M) and a force (F) are applied to a tooth at the bracket level, the type of the movement is controlled by the moment-to-force ratio (M/F) (Proffit, 1986; Tanne *et al.*, 1988). If the M/F value is equal to the distance between the bracket and the centre of resistance (CR) of the tooth, bodily movement will occur. Otherwise tipping of the tooth will take place. Location of the CR is an important factor in predicting the orthodontic tooth movement (Burstone and Koenig, 1974, 1988). Many measurements (Burstone and Pryputniewicz, 1980; Dermaut *et al.*, 1986; Pedersen *et al.*, 1991; Yoshida *et al.*, 2001; Sia *et al.*, 2007) and calculations (Jeon *et al.*, 1999; Geramy, 2000; Reimann *et al.*, 2007) have been carried out in order to determine the location of the CR.

Alternatively, until now few studies for predicting the orthodontic tooth movement based on bone remodelling have been carried out. Inoue (1989) has calculated tooth movement induced by resorption and apposition of the alveolar bone using a two-dimensional finite element

method (FEM). Alcaniz *et al.* (1998) have developed a simulation system in which two-dimensional misaligned teeth were corrected with an archwire. Bourauel *et al.* (2000) and Schneider *et al.* (2002) have calculated long-term tooth movements by three-dimensional FEMs. In addition, Bourauel *et al.* (1992) have developed a unique experimental apparatus for the simulation of three-dimensional orthodontic tooth movements. From these studies, it was found that a single tooth moved depending on the M/F ratio. Based on these studies, we assumed a bone remodelling law and calculated long-term tooth movements in some clinical cases (Kojima and Fukui, 2005; Kojima *et al.* 2007a,b) in which multiple teeth were connected with a wire. We showed that the M/F ratio acting on the teeth varied with their movement. The long-term tooth movement could not be predicted from only the initial force system.

Two important points relate to the prediction of long-term tooth movement. The first point is the bone remodelling law that moves the tooth, although it has not been yet established. The second point is the continuous change of the M/F ratio with the tooth movement. This effect should be considered when multiple teeth are connected with a wire.

In this article, we propose an alternative method for predicting long-term tooth movement. Instead of the bone

remodelling laws, we assumed that long-term tooth movement occurred as a result of the successive initial tooth movement. The tooth moved depending on the M/F ratio, which was updated with the movement. This calculation procedure was simple, but the change of the M/F ratio could be included in the simulation of long-term tooth movement.

Using this method, we simulated the canine retraction with T-loop springs. Based on the force system at the initial activation, the shape of this spring was designed to achieve bodily tooth movement over a long distance (Burstone and Koenig, 1976; Raboud *et al.*, 1997; Mazza and Mazza, 2000). Alternatively, Viecilli (2006) has calculated a variation of the force system of a T-loop spring when an anterior tooth segment moved under a fixed M/F ratio. However, the M/F ratio acting on the teeth may vary with their movement. Therefore, in this article, we simulated the long-term tooth movements produced by the T-loop springs with different bends. In addition, the tooth movement calculated using this method was compared with that calculated by the previous method (Kojima *et al.*, 2007a).

Materials and methods

Calculation model

When forces and moments act on a tooth, it moves by the elastic deformation of the PDL. This is the initial tooth movement and is calculated using the same method as that in the previous article (Kojima *et al.*, 2007a). The tooth and the alveolar bone are assumed to be rigid bodies. The calculation models of the tooth are made based on a dental study model (AM-10. Nissin Dental Products Inc., Kyoto, Japan). The PDL is assumed to be a non-linear elastic film with uniform thickness of 0.2 mm. Stress-strain curve of the PDL is approximated with two straight lines, that is, the bilinear model as shown in Figure 1. In this model, elastic moduli of the PDL are E_1 , E_2 , e_{12} in Figure 1 and Poisson's ratio ν . These elastic moduli are determined by trial and error, so as to be consistent with the initial tooth mobility of the upper first premolar measured by Goto (1971). First, assuming the E_1 , E_2 , e_{12} , and ν values, the initial tooth mobility of the upper first premolar is calculated by the

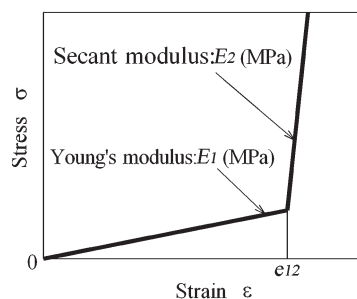


Figure 1 Bilinear elastic property (stress and strain relation) of the periodontal ligament used to calculate the initial tooth movement.

FEM. Second, these elastic moduli are modified so as to decrease the difference between the calculated result and the measured result. The E_1 controls the magnitudes of the initial high-mobility region, and the E_2 controls the following low-mobility region. The e_{12} controls the transition point of the two regions. And the ν controls the ratio of the bucco-lingual mobility to the axial mobility. The modification of elastic moduli is repeated, till the calculated tooth mobility becomes near the measured tooth mobility.

A second premolar and a first molar are used as anchorage, and a canine is distally retracted with a T-loop spring, which is designed based on the study carried out by Raboud *et al.* (1997). This spring (Figure 2A) has large bends for preventing tipping and rotation of the canine. In order to investigate the effect of the bends, a spring with small bends (Figure 2B) is also designed. These springs are made of 0.017×0.025 inch TMA (titanium molybdenum alloy) wire with Young's modulus: 69 GPa. The distance between both ends of the spring is 18.8 mm for the large bends and 20.4 mm for the small bends. These spring configurations are designed to produce retraction forces of 2 N when the spring ends are placed on the brackets. The premolar and the molar are connected with a 0.017×0.025 inch stainless steel wire (Young's modulus: 200 GPa). The spring and the wire are

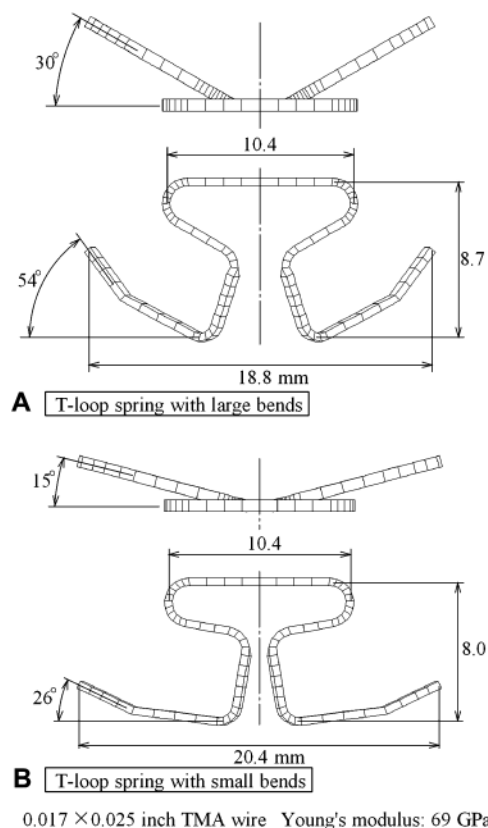


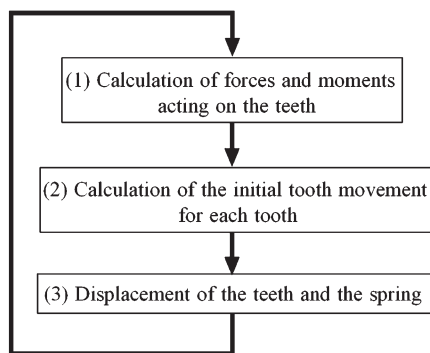
Figure 2 T-loop springs with the large bends and the small bends.

firmly ligated to the brackets to prevent sliding. Elastic deformations of the spring and wire are calculated using the FEM. The springs are divided with the three-dimensional large deformation beam elements as shown in Figure 2A and 2B.

Simulation of long-term tooth movement

Figure 3 is the simulation procedure for the long-term tooth movement, which consists of three steps. Initially, the spring is activated. That is, the spring ends are displaced to the bracket positions of the tooth. In the first step, forces (F) and moments (M) acting on the teeth, that is, the reaction forces of the spring ends, are calculated using the FEM. In the second step, the initial tooth movements of each tooth at the F and M are calculated with the tooth models. The orthodontic tooth movement is assumed to occur in the same manner as the initial tooth movement. In the third step, the teeth and the spring are displaced in the same direction of the initial tooth movements. The magnitudes of the displacement are assumed proportional to those of the initial tooth movement. The proportionality factor C is one-thousandth ($1/1000$). Namely, the tooth moves by one-thousandth of the initial tooth movement. In the preliminary calculation, when the C value was too large, the magnitude of the tooth movement became divergent in every calculation step so that stable tooth movement was impossible. This was due to the considerable change in the force produced by the large tooth movements. In contrast, when the C values were set to less than $1/1000$, the long-term tooth movements could be successfully calculated, and the same results were obtained irrespective of the C values. Iterating the above three steps, the teeth move step by step and long-term movement of the teeth is simulated. At each step, the force system acting on the teeth is updated.

We developed a computer program for the above-mentioned calculation. A pre-post processor of FEM, FEMAP V6.0 (Enterprise Software Products, Inc., Pennsylvania,



The teeth move by iteration from (1) to (3).

Figure 3 Procedure for simulating the long-term tooth movement. Tooth moves by iteration from (1) to (3).

USA) was used for illustrating the tooth movement and the spring deformation.

Results

Elastic moduli of the PDL

In Figure 4A and 4B, solid curves represent the tooth mobility of the upper canine calculated by the FEM. The elastic moduli E_1 , E_2 , e_{12} , and ν of the PDL used in the calculations are indicated in each figure. Red and blue solid circles represent the tooth mobility measured by Goto (1971). The red circles are for the bucco-lingual direction, and the blue circles are for the axial direction. The PDL I (Figure 4A) and II (Figure 4B) are correspond to the different subjects in Goto's measurements. The tooth mobility calculated using the FEM was almost the same as the measured tooth mobility.

In addition, the tooth mobility calculated with the linear elastic PDL model is indicated with the broken straight lines. Its Young's modulus and Poisson's ratio are $E = 0.13$ MPa and $\nu = 0.45$, respectively. This linear PDL model was used in the simulation of long-term tooth movements based on the previous method.

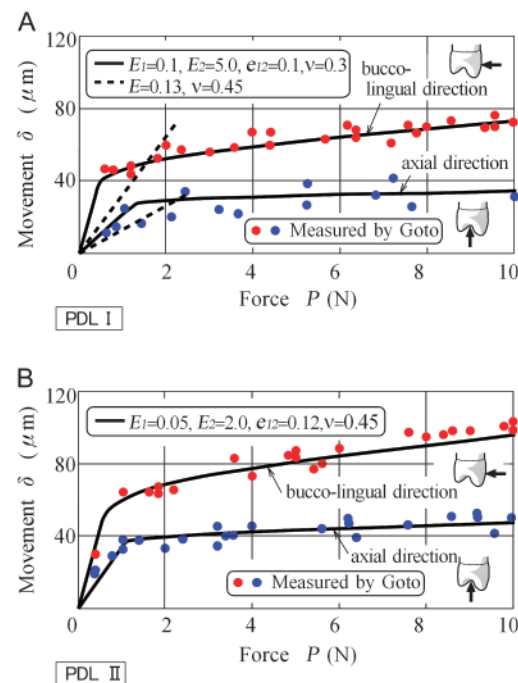


Figure 4 The initial tooth movements of the upper first premolar for estimating elastic moduli of the PDL. Figure 4A and 4B are those for different two subjects. The red and blue solid circles represent the tooth mobility measured by Goto (1971). The red circles are for the bucco-lingual direction, and the blue circles for the axial direction. The solid lines are the tooth movements calculated with bilinear PDL models, in which elastic moduli are determined so as to correspond with the measured data. The broken lines in Figure 4A are those approximated with a linear elastic PDL model.

Tooth movement produced by T-loop spring

The long-term tooth movements produced by the spring with large bends are illustrated in Figure 5 and those with small bends are illustrated in Figure 6. These were calculated using the bilinear PDL model I. In these figures, the initial positions of tooth are indicated with red lines, and the stress distributions in the PDL are illustrated with colour contour. The N is the number of iterative calculations required for

tooth movement. Magnitudes of the retraction force F , the moment-to-force ratios M_1/F and M_2/F are indicated in Figures 5 and 6.

In the case of the large bends, the canine moved bodily by 0.8 mm (Figure 5B). Next, root distal tipping of the canine occurred (Figure 5C). In the case of the small bends, at first root mesial tipping of the canine took place (Figure 6B). Then, the canine was uprighted (Figure 6C), followed by root distal tipping of the canine (Figure 6D).

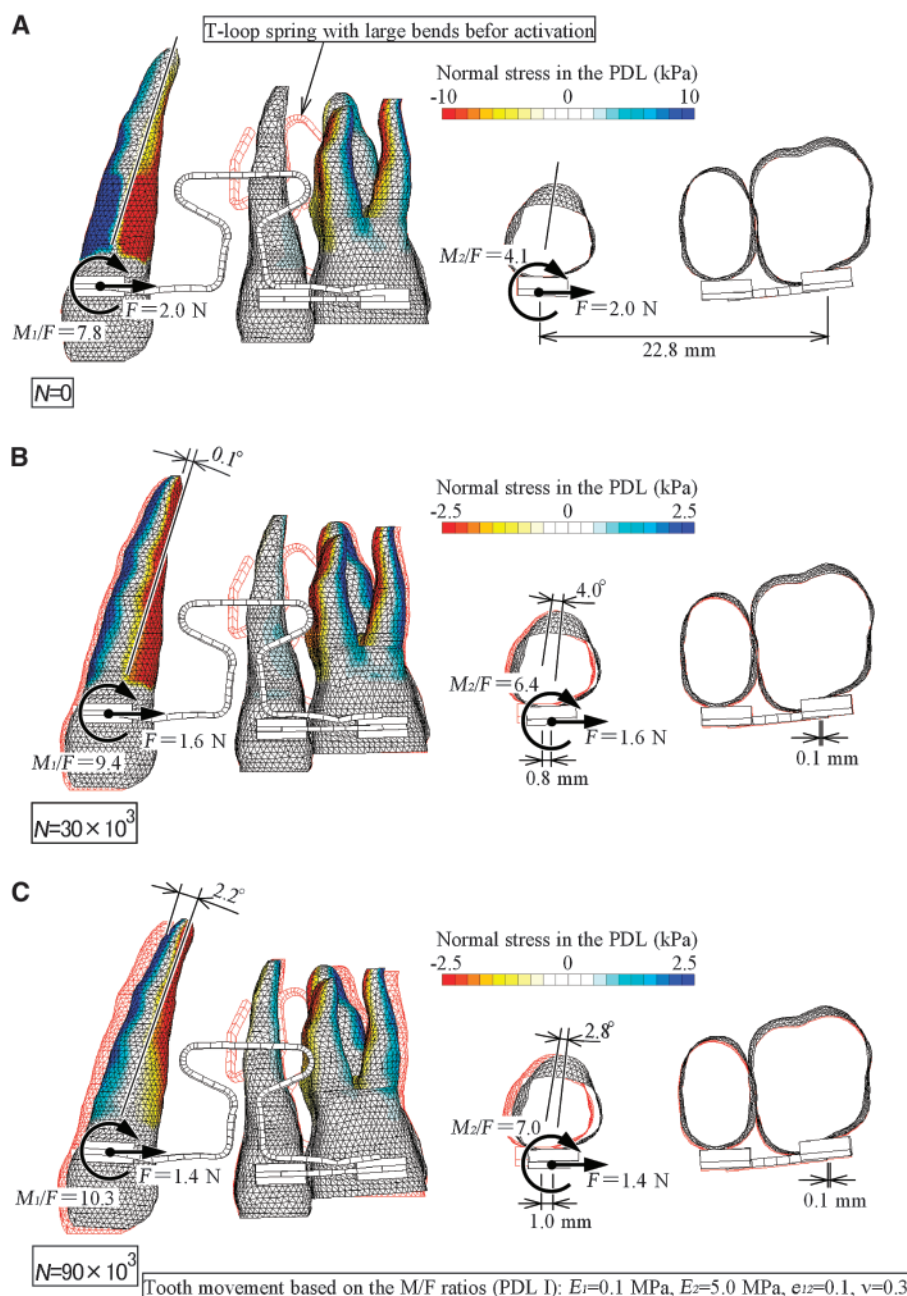


Figure 5 In the case of large bends, at first the canine moved bodily by 0.8 mm (Figure 5B), after that the canine root tipped distally (Figure 5C).

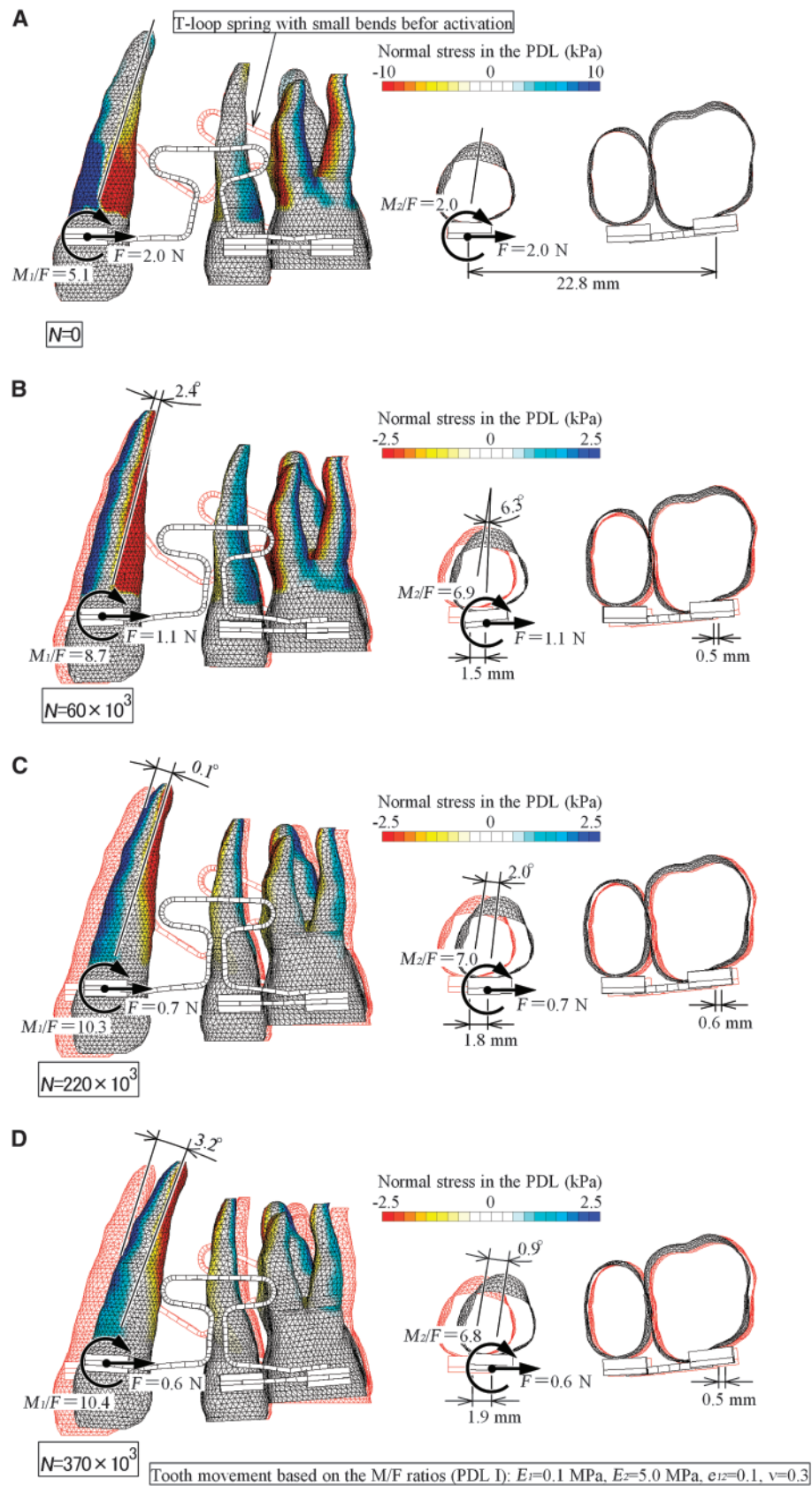


Figure 6 In the case of small bends, at first the canine root tipped mesially (Figure 6B). After that, the canine uprighted (Figure 6C) and then the root tipped distally (Figure 6D).

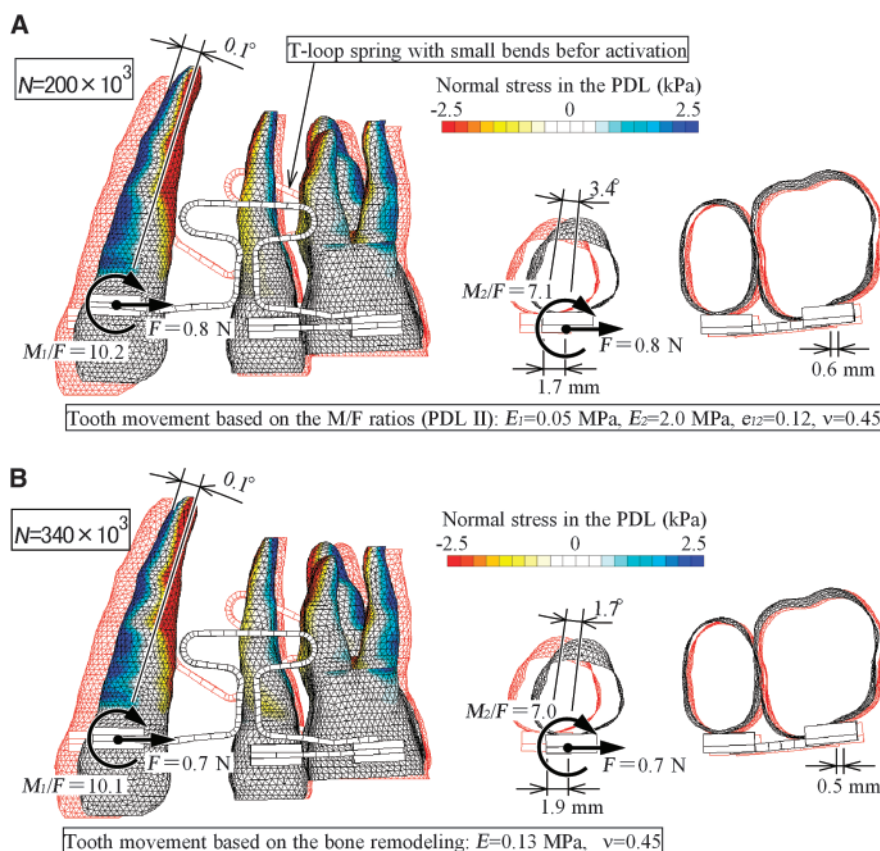


Figure 7 Tooth movement calculated by using the bilinear elastic PDL model II and that calculated by the pervious method with the linear elastic PDL model. These movements are almost the same as that calculated by using the bilinear PDL model I (Figure 6C).

In the case of the small bends, Figure 7A shows the tooth movement calculated using the bilinear PDL model II (Figure 4B), when the canine bracket moved by 1.7 mm. This result was almost the same as that calculated using the bilinear PDL model I (Figure 6C). Figure 7B shows the tooth movement calculated using the pervious method, in which the teeth moved based on the bone remodelling law. The PDL was assumed to be a linear elastic film whose elastic moduli were indicated in Figure 4A. The tooth movement in Figure 7B was almost the same as that calculated using the method presented in this article (Figure 6C).

Figures 5B, 6C, 7A, and 7B show the tooth positions when the canine bodily movement is achieved; namely tipping angle of the canine becomes almost zero, 0.1 degrees. These figures are used to indicate the ability of the T-loop springs to move the canine bodily and are compared each other.

Discussion

Tooth movement produced by T-loop spring

In the spring with large bends, the canine moved bodily in the early stage because of the appropriate moment-to-force ratios M_1/F and M_2/F . The canine could move bodily in a

distance of 0.8 mm (Figure 5B). The retraction force was decreased from 2 to 1.8 N. This decrease was not so much because the movement distance was only 0.8 mm. If it is in a clinical case, the retraction should be stopped at the time when bodily movement of the canine was achieved. As the teeth moved further, the retracting force F was decreasing. Therefore, the moment-to-force ratio M_1/F increased too large to maintain the bodily movement, and root distal tipping of the canine took place without translation (Figure 5C).

In the spring with small bends, the canine at first rotated and root mesial tipping occurred (Figure 6B) because of the insufficient moment-to-force ratios M_1/F and M_2/F . As the teeth moved further, the retraction force F was decreasing so that the M_1/F and M_2/F ratios were increasing. And the canine was uprighting and the rotation angle was decreasing. As a result, the canine could move bodily in a distance of 1.8 mm (Figure 6C). At this time, the retraction force was decreased to 0.7 N, which was about one-third of the initial retraction force, 2 N. After this time, root distal tipping of the canine took place without translation (Figure 6D).

In both springs, the moment-to-force ratios, which controlled the type of movement, were changed as the teeth

moved. Even in the small bends, the canine could move bodily after an appropriate time has elapsed. These results will not be predicted by the conventional method in which the tooth movement is estimated based on the initial force system. This is a reason for necessitating the simulation of long-term tooth movement. [Viecilli \(2006\)](#) has calculated a variation of the force system of a T-loop spring when an anterior tooth segment was tipping around a fixed centre of rotation. Such movement may not be feasible in the long term.

The actual time required for tooth movement could not be estimated using this method because dependence of the movement rate on the force magnitude has not been fully clarified. In a review written by [Quinn and Yoshikawa \(1985\)](#), it was estimated that the rate of tooth movement increased with the force at a light force level. If so, the number of iterations required for tooth movement, N , is equivalent to the elapsed time. Using this assumption, we compared the two springs. By a single activation of the spring with large bends, the canine could move bodily by 0.8 mm, and it required the number of iterations $N = 30 \times 10^3$ (Figure 5B). Alternatively, in the case of the small bends, the canine could move bodily by 1.8 mm (Figure 6C). This distance was over twice as long as that obtained by the large bends. However, the required time was $N = 220 \times 10^3$, that is, over seven times of that by the large bends. From these results, it was found that speed of the bodily tooth movement by the spring with large bends was about three times of that by the small bends. The spring with large bends can move the canine bodily faster than that with small bends, although frequent activations of the spring are necessary.

The characteristics of the two springs were compared under the same condition where the amount of the initial retraction forces was set to 2 N. This is because the amount of retraction force is a reference item for activating the spring, although we could not decide if the amount of force, 2 N, is suitable in clinical situations. Even if the amount of the initial retraction force is set to another value and characteristics of the two springs are compared, their results will be similar to those obtained in this article.

Elastic properties of the PDL

The PDL was assumed to be a bilinear elastic film with uniform thickness of 0.2 mm. And the elastic moduli of the PDL could be estimated so as to be consistent with the initial tooth mobility measured by [Goto \(1971\)](#). It was found that the bilinear elastic model was reasonable to approximate the non-linear characteristic of the initial tooth mobility. The bilinear elastic model has been used in other studies ([Vollmer et al., 1999](#); [Dorow et al., 2003](#)).

In the Goto's measurement, the initial tooth movements of the upper first premolar were measured in the two directions of the same subject. Such measurements were necessary to precisely determine the four elastic moduli of the PDL, E_1 , E_2 , e_{12} , and ν , and could not be found in other studies. This is the reason why we used the data measured by [Goto \(1971\)](#). He measured the initial mobility for five subjects. We used two data among them (PDL I in Figure 4A and PDL II in Figure 4B). Although there is a considerable difference in their movements, the cause is unknown. The shape and size of the premolar used in the measurement were not indicated in Goto's article. Hence, we made a calculation model of the premolar based on a dental study model, and the elastic moduli of the PDL I and II were estimated so as to be consistent with each tooth movement. In spite of a considerable difference in the elastic moduli, the tooth movements calculated with the PDL I (Figure 6C) were almost the same as those calculated with the PDL II (Figure 7A). This result suggested that the elastic moduli of the PDL had only slight influence on the long-term tooth movement.

Also, these tooth movements, which were calculated with the non-linear PDL models, were almost the same as that calculated using the previous method ([Kojima et al., 2007a](#)) (Figure 7B), where the PDL was assumed to be a linear elastic film (broken lines in Figure 4A) and the tooth moved based on a bone remodelling law. In these calculations, the non-linear property of the PDL and the difference of movement methods had almost no effect on the long-term tooth movement.

Simulation method of long-term tooth movement

Long-term tooth movement, in which the M/F ratios acting on the teeth changed, could be simulated by the simple method proposed in this article. The simulation results were reasonable from a mechanical perspective and provided mechanical suggestions about the T-loop springs. This method may be useful for predicting long-term tooth movement in the same way as the simulation apparatus developed by [Bourauel et al. \(1992\)](#). However, it should be noted that the validity of such simulation methods has not been demonstrated, as follows.

Mathematical models that describe the relationship between orthodontic tooth movement and applied forces have not yet been established. Therefore, we assumed that direction of orthodontic tooth movement was the same as that of the initial tooth movement at the current position. In other words, we considered biological reaction of bone remodelling that took place during orthodontic tooth movement as a black box. This is the essential assumption in our simulation method. Such treatment is reasonable and has been used for predicting a macroscopic phenomenon. For example, the macroscopic theory of elasticity, in which the microscopic behaviour of atoms is considered as a black

box, has been used successfully for calculating elastic deformation of a spring.

The calculation models of the tooth were made based on the dental study model. However, it should be noted that configuration of the tooth, especially root length, has an effect on the initial tooth movement (Geramy, 2000) and also on the long-term tooth movement.

In addition, we assumed the tooth and the alveolar bone were rigid bodies, in order to calculate the initial tooth movement. This assumption was validated by a preliminary calculation, in which the tooth and the alveolar bone were assumed to be elastic bodies.

As mentioned above, we adopted a simple principle as the first step of developing a simulation method. Although this principle is very simple, the results obtained will not necessarily be unreasonable. Even if more complicated assumptions are used in the simulation method, they cannot guarantee the validity of the method. In the present situation when microscopic mechanism of the orthodontic tooth movement has not been fully clarified, verification of the simulation method must be based on comparisons between the calculated tooth movements and those observed in clinical situations. However, clinical observations of tooth movement produced by T-loop springs were not found in other publications, so verification of this simulation should be carried in the future. If tooth movements in clinical situations are different from those simulated by this method, we will examine and modify the assumptions. By repeating such procedure, this method will be improved so that tooth movements in clinical situations can be simulated. This is the final purpose of our studies.

Conclusions

In the canine retraction with the T-loop springs, the long-term tooth movements could be simulated by a simple method proposed in this article. The force system acting on the teeth varied with their movements. Therefore, the long-term tooth movement could not be estimated from only the initial force system. The following results were obtained about the T-loop springs.

1. In the case of the large bends, the canine at first moved bodily, followed by root distal tipping. The canine could move bodily fast in a short distance.
2. In the case of the small bends, the canine at first rotated and root mesial tipping took place. Next, the canine was uprighted and the rotation angle was decreased. As a result, after a long time elapsed, the canine moved bodily at a long distance.
3. The spring with large bends can move the canine bodily faster than that with small bends, although frequent activations of the spring are necessary.

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