Biomechanical Analysis of Extraction Space Closure with Various Loop Springs Incorporated into an Archwire

Renpei Harada 1, Yukiko Yokoi 1,2,*, Aiko Kamoi 1, Rikou Miyawaki 1, Takuma Yoshida 1, Jun Kawamura 3 and Norimasa Okafuji 1

1 Department of Oral Health Promotion, School of Dentistry, Matsumoto Dental University, 1780 Hiro-Oka Gobara, Shiojiri 399-0781, Nagano, Japan
2 Department of Dental Materials, School of Dentistry, Matsumoto Dental University, 1780 Hiro-Oka Gobara, Shiojiri 399-0781, Nagano, Japan
3 Private Practice in Kawamura Dental Office, Gifu 502-0847, Gifu, Japan
* Correspondence: yukiko.yokoi@mdu.ac.jp

Abstract: The purpose of this study was to compare the mechanical efficacies of the various loop springs in the extraction space closure. The long-term movement of the teeth was simulated by the finite element method. It was assumed that the tooth moved in the same direction as the initial movement due to elastic deformation of the periodontal ligament. After the spring was activated, the initial movement was calculated, and then the alveolar socket was moved. By repeating this calculation, the teeth moved by accumulating the initial movement. The anterior teeth first tipped lingually and then became upright; thereby, the extraction space was closed for a fixed distance. In all cases, the gable bends were effective in increasing the closing speed. A higher loop increased the closing distance. When the helical loop was replaced with the vertical loop, the closing distance decreased. A spring made of thick wire increased the closing speed but decreased the closing distance. No spring increased both the closing distance and the closing speed at the same time. In clinical settings, an appropriate spring should be selected for each case by giving priority to either the closing distance or speed.

Keywords: orthodontics; loop; spring; extraction space closure; finite element method

1. Introduction

In orthodontic treatments, extraction space closure is often performed [1]. In the two-step method, the canines are moved first, and then the incisors are moved. On the other hand, in the one-step method, the canines and incisors are retracted en masse. Even with en masse retraction, movement of the anchor teeth or anchorage loss does not increase as compared with the two-step method [2,3]. En masse retraction is an easier way to close the extraction space.

Sliding mechanics or retraction springs have been used to move the anterior teeth en masse [4–7]. Both methods have advantages and disadvantages. In sliding mechanics, the anterior teeth could move bodily over a long distance because of a guide of the archwire. Friction arises when the archwire slides to the bracket slot, which decays the retraction force. In clinical situations, the magnitude of friction is uncertain, which makes it difficult to control the magnitude of the force acting on a root.

In the method with retraction springs, a force created by the spring is applied directly to the root. It is difficult to control a tipping movement of the anterior teeth due to the elastic deformation of the spring. Additionally, as the teeth move, the spring returns to its initial shape, and the force decreases, which makes it difficult to move the anterior teeth over a long distance. It is necessary to design a suitable spring for efficient bodily movement.
In many cases, loops are incorporated into an archwire and used as a retraction spring. Such archwires are also commercially available. Until now, various loops have been designed, and their force systems have been calculated by using the beam theory or the finite element method (FEM) [6–16]. However, the force system changed as the tooth moves, and the tooth movement pattern also changed [17,18]. It is difficult to estimate the efficacy of spring only from the force system created by activating the spring.

In the present study, to clarify the mechanism of tooth movement caused by the loop springs, a long-term movement of the teeth in the extraction space closure was simulated by the FEM. First, it was shown how the teeth were moved with the retraction spring, and then how the loop shape and the wire size affected the movement. Lastly, the mechanical efficacies of various springs were compared to each other.

2. Materials and Methods
2.1. FEM Model

Figure 1 shows the FEM model, in which the anterior teeth were moved distally to close an extraction space with a helical loop incorporated into an archwire. The only right side was modeled due to the bilateral symmetry.

![Figure 1. Finite element model for simulating extraction space closure using helical loop spring.](image)

Three-dimensional models of the teeth were made based on a dental study model (i21D-400C, Nissin Dental Products Inc., Kyoto, Japan). The teeth were assumed to be rigid bodies because their elastic deformations were negligible compared to that of the periodontal ligament (PDL). The surface of the tooth was divided with rigid shell elements. The PDL of 0.2 mm thickness was constructed over the root with solid elements. It was assumed to be an elastic material, which has a linear stress–strain relationship (Young's modulus: 0.13 MPa, Poisson's ratio: 0.45) [18]. By using these elastic moduli, the in vivo mobility of human teeth could be simulated by the FEM.

The archwire of 0.016 × 0.022 inches (0.41 × 0.56 mm) or 0.018 × 0.025 inches (0.46 × 0.64 mm) is made of a low elasticity material, TMA (Titanium Molybdenum Alloy, Young's modulus: 69 GPa) [19]. The low elastic wire was used to reduce the spring constant and increase the amount of tooth movement, which facilitated visual observations of the movement patterns. A decrease in the elastic modulus of a wire is mechanically equivalent to a decrease in wire size. The archwire was divided with three-dimensional beam elements and fixed to the crown with rigid beam elements. While brackets were not modeled, this boundary condition simulated the case where the archwire was firmly ligated without a clearance gap to the bracket slot.
A helical or vertical loop was incorporated into the archwire between the canine and the premolar. The height of the loop was 6, 8, and 10 mm. The posterior part of the archwire was bent 10, 20, and 30° for preventing lingual tipping of the anterior teeth, which was called gable bend (GB).

2.2. Activation of Spring

After the anterior teeth were fixed to the archwire, its distal part was leveled with the bracket and then translated distally and fixed to the premolar. The amount of distal translation was defined as the amount of activation. By activating the spring, a mesial force and clockwise moment acted on the premolar. The magnitude of the mesial force is the same as that of the distal force applied to the anterior teeth. After the activation, the archwire was fixed to the molars.

In the FEM simulation, when the amount of activation is increased, the force acting on the anterior teeth increases, which allows the teeth to move speedily over a long distance. However, in clinical situations, an excessive force may cause root resorption or hyalinization of the PDL, which impedes tooth movement. The appropriate amount of force for tooth movement has not been clarified.

In the present study, the amount of activation was adjusted so that the initial force applied to the anterior teeth was 2 N. This amount was selected as a typical one [1]. Under this condition, the efficacies of the springs were compared to each other.

2.3. Simulation for Long-Term Tooth Movement

When a force is applied to a tooth, it moves due to elastic deformation of the PDL, which is called the initial movement. When maintaining the force, mechanical stimuli to the PDL induce remodeling of the alveolar bone, which causes movement of the alveolar socket. This is the orthodontic movement. Its process was simulated by the FEM.

Figure 2 shows the calculation procedure, in which the alveolar socket was moved based on the initial movement [18]. First, the spring was activated. Next, the initial movement was calculated. Lastly, the alveolar socket was moved in the same direction and the same amount as the initial movement. When repeating these calculations, the teeth moved with the alveolar sockets by accumulating the initial movements. The force system acting on the teeth was updated with each repetition. The number of repeated calculations, \( N \), corresponded to the elapsed time. However, \( N \) could not be converted into the actual time, because the time required for the movement of the alveolar socket has not been clarified in clinical situations.

![Diagram](image-url)

**Figure 2.** Procedure for simulating orthodontic tooth movement.
In the initial movement, the deformation of the alveolar bone was negligible, thereby assuming the alveolar bone to be a rigid body. The movement of the alveolar socket was performed by displacing the nodes on the outer surface of the PDL. As a result, the alveolar bone became unnecessary for the simulation and was not included in the FEM model.

Similar simulation methods for long-term tooth movement have been successfully applied to various cases in orthodontics [19–27]. A FEM software (ANSYS 11.0, Ansys Inc., Canonsburg, PA, USA) was used for the simulation.

3. Results

Figure 3 shows the tooth movement process under the reference condition, that is, an archwire of 0.016 × 0.022 inch, a helical loop with a height of 8 mm, and a gable bend of 20°. Although brackets were not included in the FEM model, their dummies were drawn to indicate the space occupied by the brackets. The mean stress in the PDL is depicted on the root with color contours.

When the spring was activated (Figure 3A), a mesial force of 2 N, an intrusive force of 0.3 N, and a moment of 9.4 N-mm were applied to the premolar. A distal force of 2 N and a moment of 5.7 N-mm were applied to the anterior teeth. The maximum equivalent stress of 770 MPa was raised in the spring, which was less than the yield stress of TMA (1010 MPa) [28]. After the activation, the teeth moved with repeated calculations. At \( N = 500 \) (Figure 3B), the canine tipped lingually 5.5°, and its crown moved distally 2.1 mm. The central incisor tipped lingually 7.9°. The premolar tipped mesially 2.7°, and its crown moved mesially 0.4 mm. At \( N = 2700 \) (Figure 3C), the tipping angle of the canine was reduced to 0.1°, at which the anterior teeth were considered to translate or move bodily. The number of repeated calculations required for the bodily movement was denoted by \( N_b \). The canine and the premolar moved distally 1.8 mm and mesially 0.6 mm, respectively. The sum of them, 2.4 mm, is the space closing distance, which was denoted by \( C \). At \( N = 4000 \) (Figure 3D), the canine deviated from bodily movement and tipped labially. The tipping angle of −2.6 means the canine tipped labially 2.6°. On the labial side of the anterior tooth, the stress at the root apex changed from compression to tension, depending on the movement pattern.

Figure 4 shows the bodily movement of the canine when the gable bend was changed to 10° and 30°. As the gable bend increased, \( N_b \) and \( C \) decreased. The tipping angle of the premolar increased.

Figure 5 shows the case when the loop height was changed to 10 mm and 6 mm. As the loop height decreased, \( N_b \) and \( C \) and the tipping angles of the premolars and central incisor decreased.
Figure 3. Tooth movement process with the helical loop spring. The anterior teeth first tip, then become upright. At $N_b = 2700$, the canine achieves bodily movement.
When the spring was activated (Figure 3A), a mesial force of 2 N, an intrusive force of 0.3 N, and a moment of 9.4 N·mm were applied to the premolar. A distal force of 2 N and a moment of 5.7 N·mm were applied to the anterior teeth. The maximum equivalent stress of 770 MPa was raised in the spring, which was less than the yield stress of TMA (1010 MPa) [28]. After the activation, the teeth moved with repeated calculations. At $N = 500$ (Figure 3B), the canine tipped lingually 5.5°, and its crown moved distally 2.1 mm. The central incisor tipped lingually 7.9°. The premolar tipped mesially 2.7°, and its crown moved mesially 0.4 mm. At $N = 2700$ (Figure 3C), the tipping angle of the canine was reduced to 0.1°, at which the anterior teeth were considered to translate or move bodily. The number of repeated calculations required for the bodily movement was denoted by $N_b$. The canine and the premolar moved distally 1.8 mm and mesially 0.6 mm, respectively. The sum of them, 2.4 mm, is the space closing distance, which was denoted by $C$.

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Figures 6 and 7 show the cases where the wire size was increased to 0.018 × 0.025 inch and the helical loop was replaced with the vertical loop, respectively. In both cases, $N_b$, $C$, and the tipping angle of the central incisor decreased compared to the reference condition (Figure 3C).

Using the number of repeated calculations required for the bodily movement, $N_b$, and the achieved space closing distance, $C$, we defined a parameter $C/N_b$ that expressed the space closing speed. The relationship between $C/N_b$ and $C$ is shown in Figure 8.
Figure 5. Effect of loop height. When loop height decreases, closing distance $C$ and the number of repeated calculations $N_b$ decreases.

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Figure 6. Effect of the wire size. When the wire size increases, closing distance $C$ and the number of repeated calculations $N_b$ decreases.
Figure 7. Replacement of helical loop with a vertical loop. Closing distance $C$ and the number of repeated calculations $N_b$ decreases.

Using the number of repeated calculations required for the bodily movement, $N_b$, and the achieved space closing distance, $C$, we defined a parameter $C/N_b$ that expressed the space closing speed. The relationship between $C/N_b$ and $C$ is shown in Figure 8.

4. Discussion

4.1. Mechanism of Extraction Space Closure

At the activation of the spring, the moment-to-force ($MF$) ratio acting on the anterior teeth was $5.7 \text{ N-mm}/2 \text{ N} = 2.9 \text{ mm}$, which was insufficient for bodily movement (Figure 3A). This was due to the elastic deformation of the archwire. Firstly, the anterior teeth tipped lingually and moved distally (Figure 3B). It led to a decrease in the retraction force exerted by the spring, which increased the $MF$ ratio. The anterior teeth began upright and moved bodily at which the tipping angle of the canine decreased to almost zero (Figure 3C). At that time, the incisors were still tipped lingually due to the elastic deformation of the archwire. For the same reason, the molars slightly tipped mesially. After that, the canine deviated from bodily movement and tipped labially (Figure 3D).

As described above, a bodily movement of the anterior teeth was achieved as a result of the tipping and upright. The crowns first moved by the tipping and did not
move during the upright. This movement process was the same as those in other traction springs [17,18,27].

In the reference condition (Figure 3), the extraction space could be closed by 2.4 mm with a single activation of the spring. Since the initial extraction space is about 7 mm, it will be closed completely with three activations.

In the en masse retraction of the anterior teeth, since all teeth are fixed to an archwire, the teeth hardly rotate on their axes. In the first step of the two-step retraction, only the canine is moved bodily with a retraction spring. At that time, it is necessary to control not only tipping but also axial rotation. The two-step retraction is more complicated than the en masse retraction.

4.2. Effects of Loop Shape and Wire Size

When the gable bend was increased, the repeated calculations required for the space closure, \( N_b \), decreased remarkably. This was because a moment acting on the anterior teeth was increased by the gable bend. The larger moment reduced the tipping angle that occurred early in the space closure. Thereby, the anterior teeth could be upright with a small number of repeated calculations.

When decreasing the loop height or increasing the wire size or replacing the helical loop with the vertical loop, the spring constant, or stiffness of the loop increases. In these cases, to limit the retraction force to 2 N, it was necessary to reduce the amount of activation, which decreased the closing distance \( C \).

When increasing the wire size to \( 0.018 \times 0.025 \) inches, the spring constant increased; thereby, the closing distance \( C \) decreased. In addition, because the elastic deformation of the whole archwire became smaller, the tipping angle of the central incisor decreased.

The mechanical properties of a spring depend on the flexural rigidity \( EI \), in which \( E \) is Young’s modulus, and \( I \) is the moment of inertia of the cross-sectional area [29,30]. For the rectangular wire of depth \( h \) and width \( b \), \( I = bh^3/12 \). When the wire size increases from \( 0.016 \times 0.022 \) to \( 0.018 \times 0.025 \) inches, \( I \) increase 1.6 times. This effect is roughly equivalent to changing the material of the \( 0.016 \times 0.022 \)-inch wire from TMA (\( E = 69 \text{ GPa} \)) to a titanium alloy (\( E = 1000 \text{ GPa} \)).

4.3. Comparison of Space Closing Efficacy between Various Loop Springs

The parameter \( C/N_b \) corresponds to the space closing speed. However, it did not verify whether \( C/N_b \) is proportional to the closing speed in clinical settings. For example, when \( C/N_b \) is doubled, it is unknown whether the closing speed is doubled. It could only be predicted that the larger \( C/N_b \), the faster the closing speed. We used \( C \) and \( C/N_b \) to compare the efficacies of various springs.

In Figure 8, the spring plotted on the right side allowed a longer closing distance and on the upper side allowed a faster closing speed. A spring that can move speedily over a long distance must be plotted in the upper right area in Figure 8, but no such springs existed. In clinical settings, an appropriate spring should be selected for each case by giving priority to either the closing distance or speed.

For all springs, when the gable bend was increased, although the closing distance \( C \) decreased, the closing speed \( C/N_b \) increased significantly. It was concluded that the gable bend was very effective for speedy space closure. It should be noted that an excessive gable bend causes plastic deformation of the spring during the activation.

When the helical loop was replaced with the vertical loop, the closing distance \( C \) decreased. On the other hand, when the loop height was increased, \( C \) increased. In both cases, the change in \( C/N_b \) was not significant. To increase the closing distance without a significant decrease in closing speed, the loop should be made as high as possible. However, if the loop is too high, it will be uncomfortable for the patient.

When the wire size was increased to \( 0.018 \times 0.025 \) inches, the closing speed \( C/N_b \) increased, but the closing distance \( C \) decreased. Since an increase in wire size is equivalent
to an increase in Young’s modulus, the closing speed increases when the spring is made of stainless steel with a larger Young’s modulus (200 GPa).

So far, the moment-to-force ratio has been used to evaluate the mechanical property of a retraction spring. However, in the present simulation, the force system and the resulting movement pattern changed as the teeth moved. Hence, we attempted to evaluate the space closing efficacy based on the long-term movement of the teeth. Although this method is slightly more advanced than before, its validity must be verified in the future.

4.4. Finite Element Simulation

In the present FEM, the long-term tooth movement could be simulated under various assumptions. Their validities have been discussed in the previous articles [17–22]. The most basic assumption is that the tooth movement occurs in the same direction as the initial movement, which is caused by elastic deformation of the PDL. This assumption is consistent with clinical experiences. That is, when a force is applied to the crown, a tipping movement occurs. When a moment is applied together with the force, the tooth can move bodily. This change in movement pattern is observed in both initial and orthodontic tooth movements.

The tooth moved by repeating the initial movement. The number of repetitions, $N$, which should correspond to the elapsed time, could not be converted to actual time. This is because the relationship between the amount of initial movement and the rate of orthodontic movement has not been clarified in clinical settings. Hence, the treatment period cannot be predicted by the present FEM simulation.

In the present FEM model, the bracket was excluded, and the archwire was fixed directly to the crown. This corresponds to the case where the archwire is firmly fixed into the bracket slot without a clearance gap. Under this reference condition, the efficacies of various springs were compared. In the actual case where there is a clearance gap between the archwire and the bracket slot, the archwire moves in the gap, and thereby the tooth tips [24,25]. The amount of the tipping movement depends on the relative initial position of the bracket slot and archwire, which is unknown in clinical settings. At present, it is difficult to include the clearance gap in the FEM model.

In clinical settings, forces act on the maxillary teeth not only from the orthodontic appliances but also from the cheeks, tongue, and mandibular teeth. These forces may affect tooth movement but were neglected in the present FEM. This is a limitation of the present study.

5. Conclusions

Tooth movements in the extraction space closure with loop springs incorporated into an archwire were simulated using the FEM. The following conclusions were drawn from the simulation results.

1. The anterior teeth first tipped lingually then became upright. The bodily movement of the anterior teeth was achieved by two movement patterns, tipping and upright.
2. When the loop height was increased from 6 to 8 mm, the distance of bodily movement increased.
3. When the gable bend was increased from 10 to 30°, the speed of bodily movement increased.
4. When the wire size was increased from $0.016 \times 0.022$ to $0.018 \times 0.025$ inches, the speed of bodily movement increased, but the distance of bodily movement decreased.
5. When the helical loop was replaced with the vertical loop, the distance of bodily movement decreased.

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