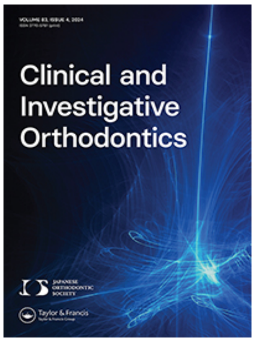



Clinical and Investigative Orthodontics

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/todw21


# Effect of archwire dimensions in combination with different extraction space widths on tooth movement during space closure in sliding mechanics: long-term 3D finite element analysis


**Patrick El Sayegh , Runa Yamagushi , Roland Kmeid , Nabil Ghosn , Hiroya Komaki , Ryo Hamanuka , Noriaki Yoshida & Joseph Bouserhal**



**To cite this article:** Patrick El Sayegh , Runa Yamagushi , Roland Kmeid , Nabil Ghosn , Hiroya Komaki , Ryo Hamanuka , Noriaki Yoshida & Joseph Bouserhal (16 Apr 2025): Effect of archwire dimensions in combination with different extraction space widths on tooth movement during space closure in sliding mechanics: long-term 3D finite element analysis, Clinical and Investigative Orthodontics, DOI: 10.1080/27705781.2025.2491897

**To link to this article:** https://doi.org/10.1080/27705781.2025.2491897





Published online: 16 Apr 2025.

CLINICAL AND INVESTIGATIVE ORTHODONTICS
https://doi.org/10.1080/27705781.2025.2491897

JAPANESE ORTHODONTIC SOCIETY
Taylor & Francis
Taylor & Francis Group

OPEN ACCESS
Check for updates

# Effect of archwire dimensions in combination with different extraction space widths on tooth movement during space closure in sliding mechanics: long-term 3D finite element analysis

Patrick El Sayegh[a,b], Runa Yamagushi[c], Roland Kmeid[a,b], Nabil Ghosn[b], Hiroya Komaki[c], Ryo Hamanuka[c], Noriaki Yoshida[c] and Joseph Bouserhal[a,b]

[a]Department of Orthodontics, Saint Joseph University of Beirut, Beirut, Lebanon; [b]Craniofacial Research Laboratory, Research Assistant, Faculty of Dental Medicine, Saint Joseph University of Beirut, Beirut, Lebanon; [c]Department of Orthodontics and Dentofacial Orthopedics, School of Biomedical Sciences, Nagasaki University, Nagasaki, Japan

**ABSTRACT**

**Purpose:** The objective of this study was to investigate the long-term effect of different archwire dimensions in combination with different extraction space widths on the biomechanical behaviour of tooth movement during space closure using sliding mechanics.

**Materials and Methods:** A finite element model of the maxillary dentition was constructed with 0.022 × 0.028-in brackets and three different archwires of 0.017 × 0.025-in, 0.018 × 0.025-in, and 0.019 × 0.025-in. The extraction space was set as 4 or 7 mm. En-masse retraction was performed by applying a retraction force from 4 mm power arm. We compared the degree of labio-lingual tipping of the central incisor, mesio-distal tipping of the canine, mesio-distal and bucco-lingual tipping of the first molar, rotation of the occlusal plane and the velocity of space closure when varying the archwire dimesions in combination with different extraction space widths.

**Results:** The central incisor showed lingual crown tipping for all three archwire dimensions even with 4 mm power arm. The larger the archwire dimension, the less substantially the incisor tipped lingually. The first molar showed lingual tipping with small size archwires. The wider the residual extraction space, the more substantially the central incisor tipped lingually.

**Conclusions:** The larger the archwire dimension, namely, the better controlled tooth movement we try to achieve, the longer the treatment duration is required.

**ARTICLE HISTORY**
Received 26 February 2024
Revised 12 March 2025
Accepted 4 April 2025

**KEYWORDS**
Tooth movement; finite element method; sliding mechanics; space closure; friction

## Introduction

Crowded, irregular, or protruding teeth have been a problem for some individuals since antiquity and attempts to correct this disorder go back at least to 1000 BC [1]. In many cases, extracting teeth is necessary to provide space on the dental arch and align the teeth correctly. Teeth extraction is a popular orthodontic method used to reduce crowding or achieve maximal interarch interdigitation. The use of orthodontic appliances to close the extraction space is usually achieved in one of the two ways. Closing loops in a continuous or segmented archwire is one way to do it. The loop is activated with a distalizing force after the wire is engaged in the brackets. The second technique, sliding mechanics, involves pushing or pulling a tooth along a continuous archwire with a force delivery system adequate to produce and sustain movement. Generally, either a coil spring or a form of elastomeric material is used to accomplish the latter [2]. The efficacy of this mode of space closure, however, may be hampered by friction. There are a variety of factors that can produce friction. They include, among others, bracket slot width, bracket composition, wire size, wire composition, wire-to-slot ligation method, interbracket distance, and relative interface motion between the bracket and the archwire [3–5].

The use of the finite element method in structural engineering seeks to determine the state of tension and deformation of an arbitrary-geometry solid subjected to external forces. This type of calculation has the generic designation of analysing structures [6]. The finite element method has revolutionized orthodontic biomechanical research [7–10]. Actually, it is a non-invasive, precise way for obtaining quantitative and detailed information about physiological responses in tissues like the periodontal ligament and alveolar bone [11].

Many studies [12,13] evaluated the different factors influencing the efficiency of sliding mechanics to close an extraction space and the effect of sliding mechanics on the dentition. Kojima et al. [14] studied the anterior effects of space closure without the use of a power

**CONTACT** Patrick El Sayegh patrickelsayegh@hotmail.com Department of Orthodontics, Saint Joseph University of Beirut, Mansourieh, Mount Lebanon

arm, while others, like Tominaga et al. [15] used an 0.018-inch bracket slot, and to our knowledge, there has been no previous study that evaluated the tooth movement pattern when varying the archwire dimension and/or width of the residual extraction space and changes in rotation of the occlusal plane.

The objective of this study was to compare the degree of labio-lingual tipping of the central incisor, mesio-distal tipping of the canine, mesio-distal and bucco-lingual tipping of the first molar, rotation of the occlusal plane and the velocity of space closure when varying the archwire dimensions in combination with different extraction space widths using the finite element method.

## Materials and methods

While loading the different configurations of the maxillary model, we simulated a first premolar extraction space closure using three different stainless-steel archwires of 0.017 × 0.025-in, 0.018 × 0.025-in, and 0.019 × 0.025-in.

### *Model preparation*

As stated by Hamanaka et al. [16], the authors used the same methodology used in their article in order to simplify the model creation:

To obtain 3-dimensional (3D) images of a maxillary dentition, a dry skull was scanned using a multi-image microcomputed tomography scanner (3DX; J. Morita, Kyoto, Japan) with a voxel size of 80 µm [10]. Image data were then exported as a digital imaging and communication in medicine (DICOM) file into a 3D image processing and editing software (Mimics 10.02; Materialise, Leuven, Belgium) [10]. After reconstructing the DICOM file to the 3D surface data, results were inputted as 3-node triangular elements into finite element preprocessing and postprocessing software (Patran 2012.1; MSC Software, Los Angeles, Calif.) and were converted to 4-node quadrilateral elements. After the model was meshed again, the teeth were aligned to the ideal positions of the normal dentition (the teeth were arranged so that the axis of each tooth relative to the occlusal plane was standard). Then, the first premolar was removed assuming the extraction is indicated. A symmetrical model of the maxillary dentition was developed to reduce the number of elements [10]. Orthodontic tooth movement was simulated using the bone remodelling algorithm [10–12] on the assumption that there is a good correlation between the rate of bone remodelling and the initial tooth displacement. The initial displacement is produced after an orthodontic force is applied to the tooth model in the first step. In the second step, the deformed periodontal ligament is restored to its original configuration and thickness of 0.2 mm. These two steps (i.e. initial displacement and bone remodelling) are iterated to reproduce the bone remodelling process [17]. The number of bone remodelling steps indicates the treatment duration required to close the extraction space. In other words, fewer bone remodelling steps result in faster space closure, and more steps result in slower space closure.

The occlusal plane was set based on the incisal edge of the central incisor and the mesial buccal cusp of the first molar, and the degree of clockwise rotation from the initial position was measured as the change in the angle of the occlusal plane.

The tooth model was constructed using shell elements with a thickness of 3 mm to develop a more simplified model for reducing analysis time [10]. Young's modulus was set to 204 GPa. This assumed that the tooth is barely deformed because the orthodontic force is small, resulting in only a small amount of tooth deformation, which can be negligible. Poisson's ratio was also assigned a value of 0.3. The periodontal ligament (PDL) was constructed on a root surface using 8-node hexahedral elements with a uniform thickness of 0.2 mm [16,17], a Young's modulus from 0.03 to 0.3 Mpa (bilinear) and a Poisson's ratio of 0.3.

The fixed orthodontic appliance comprised 0.022 × 0.028-in slot brackets and a 0.017 × 0.025-in, 0.018 × 0.025-in and 0.019 × 0.025-in stainless steel archwire with a Young's modulus of 204 GPa and a Poisson's ratio of 0.3 (Figure 9). The extraction space was closed by using a NiTi coil spring delivering 150 g (1.5 N) of force [14] extending from the first molar to a 4 mm power arm soldered distally to the bracket of the lateral incisor [15,16]. The coefficient of friction between the bracket slots and archwire was assumed to be 0.2 [18–20]. All materials employed for the finite element model were taken to be isotropic, homogenous, and linearly elastic. All analyses were performed using a finite element package [21,22] (Marc 2016; MSC Software). Figure 1 shows a symmetrical finite element model of the maxillary dentition. The extraction space was set as 4 or 7 mm. Figure 2 shows the orientation of the retraction and reaction forces from occlusal, lateral and frontal views.

## Results

### *Lingual crown tipping of the central incisor*

Figure 3 shows the relationship between the degree of lingual crown tipping and translational displacement at the centre of resistance (CR) of the central incisor in the lingual direction when the residual extraction space was assumed to be 4 mm after levelling. We noticed that the larger the wire dimension, the less the lingual crown tipping of the central incisor was produced (8.5° for the 0.019 × 0.025-in and 10.6° for

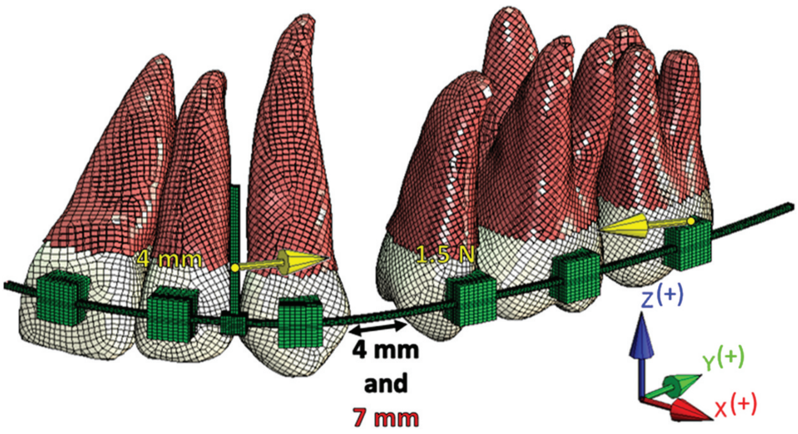


**Figure 1.** Three-dimensional symmetrical finite element model of the maxillary dentition. The extraction space was set as 4 or 7 mm.

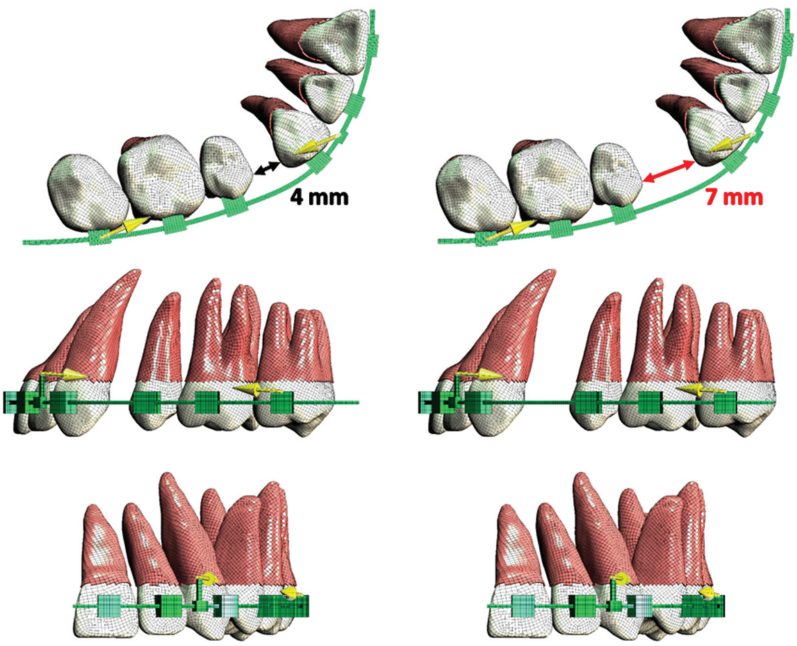


**Figure 2.** Orientation of the retraction and reaction forces from occlusal, sagittal and frontal views. The left is when the space is 4 mm, and the right is when the space is 7 mm.

the 0.017 × 0.025-in) and on the other hand, the larger the wire size, the greater the lingual displacement of the central incisor (1.9 mm for the 0.019 × 0.025-in and 1.7 mm for the 0.017 × 0.025-in. However, there was only a slight difference in the degree of lingual crown tipping of the central incisor between 0.017 × 0.025-in and 0.018 × 0.025-in. Although tipping tendency gradually increased all through the space closure with the 0.017 × 0.025-in and 0.018 × 0.025-in, the increment rate for incisor tipping decreased in the last phase of space closure with the 0.019 × 0.025-in.

There was an obvious difference in the degree of lingual inclination of the central incisor between 0.017 × 0.025-in and 0.018 × 0.025-in with extraction space of 7 mm, although we found only a small difference in the tipping tendency between the two archwire dimensions in case of extraction space of 4 mm. When the extraction space was considered to be 4 mm, the 0.019 × 0.025-in archwire has started binding against the edge of the bracket slot, namely, the diagonal corners of cross-section of the archwire came into contact with the bracket slot (Figure 3), and then the incremental rate in the degree of tipping decreased in the latter phase of space closure. In contrast, the archwire and bracket contacted at only one point with the 0.017 × 0.025-in and the 0.018 × 0.025-in, wherein no binding occurred under the conditions of this analysis. When the extraction space was considered to be 7 mm, the binding occurred during space closure for all archwire dimensions (Figure 4). When comparing the effect of extraction space width on the degree of lingual crown tipping, the central incisor showed greater tipping with the extraction space width of 7 mm than 4 mm (Figure 5).

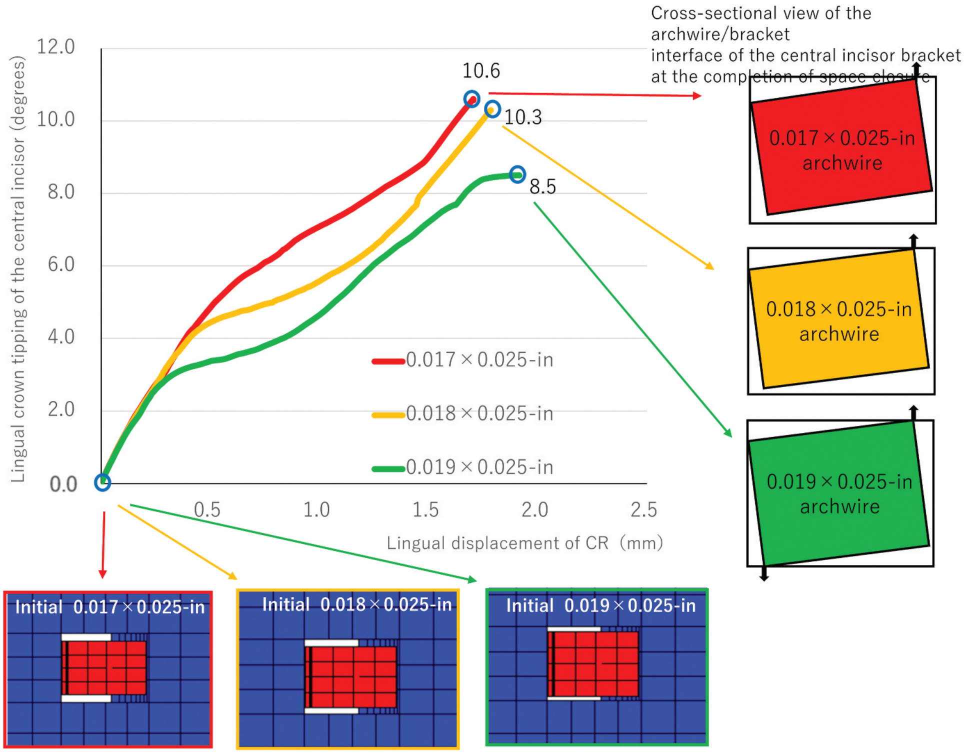


**Figure 3.** Degree of lingual crown tipping as a function of translational displacement at CR of the central incisor in the lingual direction when the residual extraction space was assumed to be 4 mm after levelling. Cross-sectional views of the archwire/bracket interface of the central incisor bracket at the beginning of space closure were shown below, those at the completion of space closure on the right. Arrows at corners of the wire cross-section indicate normal forces generated at the contact points between the archwire and incisor brackets.

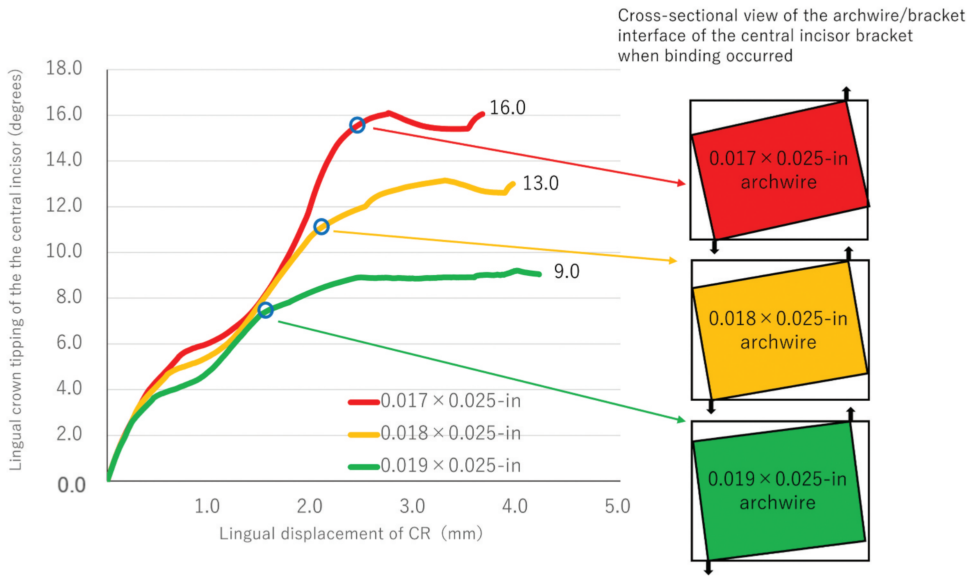


**Figure 4.** Degree of lingual crown tipping as a function of translational displacement at CR of the central incisor in the lingual direction when the residual extraction space was assumed to be 7 mm after levelling. Cross-sectional views of the archwire/bracket interface of the central incisor bracket at a time when binding occurred on the right.

### *Distal tipping of the canine*

As the canine moved distally, the degree of distal tipping of the CR of the canine increased in all cases. The canine showed greater tipping with the extraction space width of 7 mm than 4 mm. The larger the wire dimension, the less the tendency for distal tipping of the canine. When the extraction space was considered to be 4 mm, the difference in the degree of distal tipping of the canine between the 0.017 × 0.025-in and the 0.018 × 0.025-in was small. When the extraction space was considered to be 7 mm, the degree of distal tipping of the canine gradually increased all through the space closure with the 0.017 × 0.025-in and 0.018 × 0.025-in.

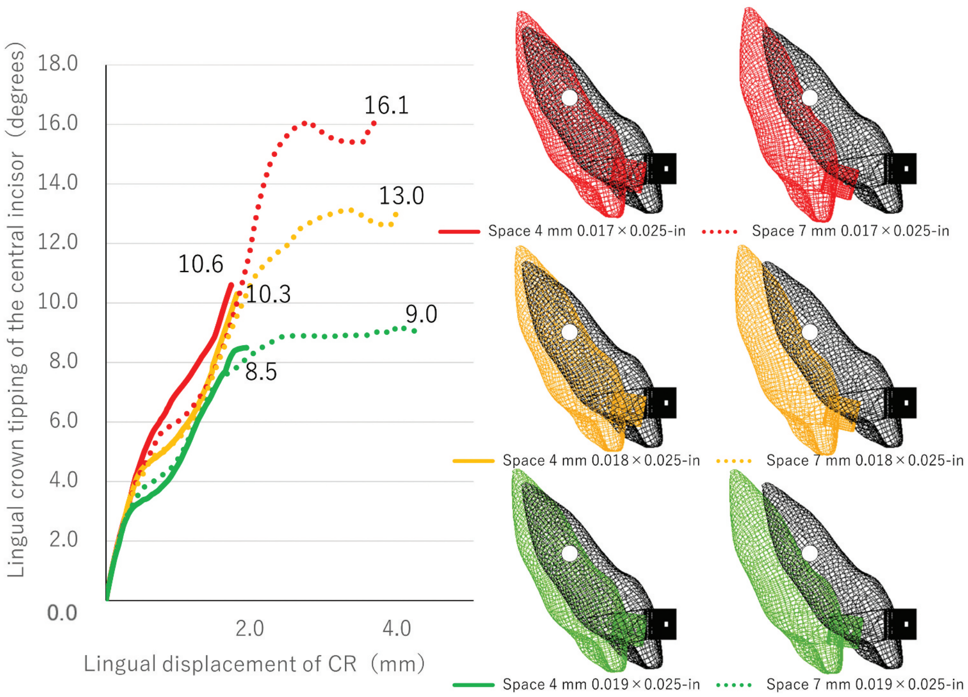


**Figure 5.** Degree of lingual crown tipping as a function of translational displacement at CR of the central incisor in the lingual direction when the residual extraction space was assumed to be 4 and 7 mm.

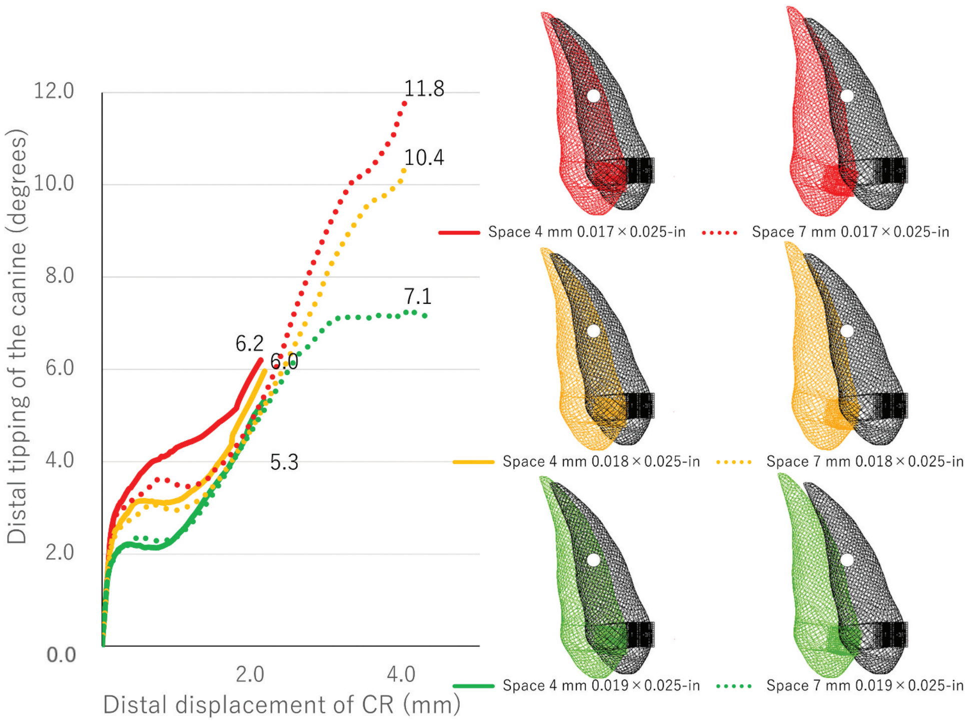


**Figure 6.** Degree of distal tipping as a function of translational displacement at CR of the canine in the distal direction when the residual extraction space was assumed to be 4 and 7 mm.

However, with the 0.019 × 0.025-in, the incremental rate in the degree of distal tipping decreased in the latter phase of space closure (Figure 6).

### *Mesio-distal tipping of the first molar*

Since there was only a little difference in the tipping tendency of the first molar with the extraction space of 4 and 7 mm, only the results with the extraction space of 4 mm were shown regarding mesio-distal and lingual tipping. The degree of mesial tipping of the first molar rapidly increased in the initial phase, and then declined after the peak. At the completion of the space closure, the first molar showed distal tipping regardless of the archwire dimension. Similar results were found regarding the second molar (Figure 7).

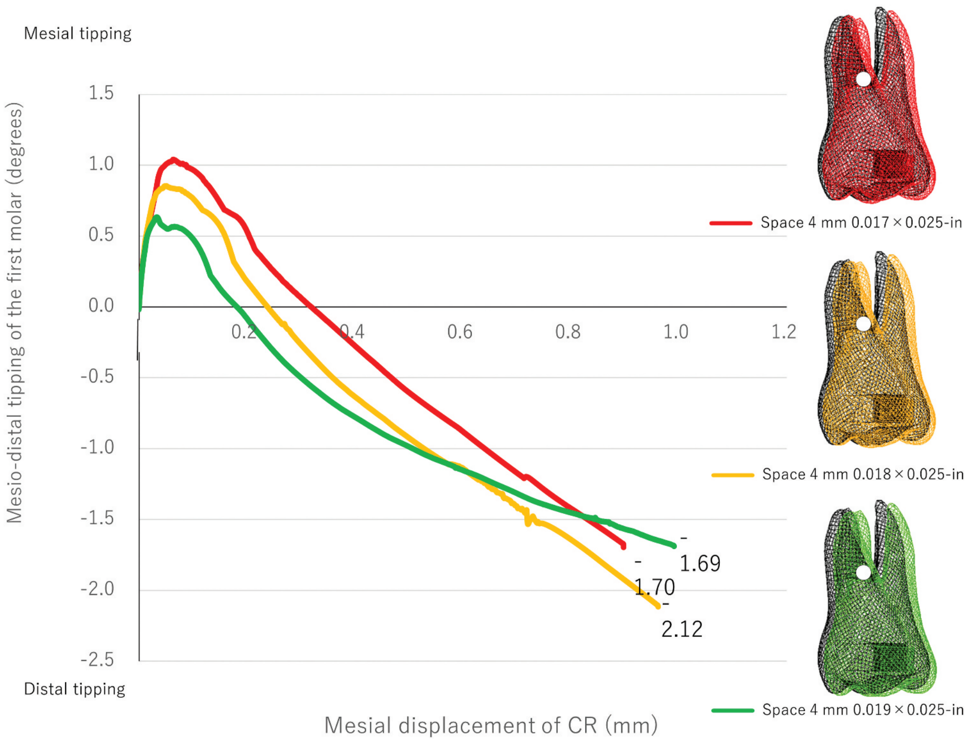


**Figure 7.** Degree of mesio-distal tipping as a function of translational displacement at CR of the first molar in the mesial direction when the residual extraction space was 4 mm.

### *Lingual tipping of the first molar*

The relationship of tipping to translational displacement showed curves with two peaks for all archwire dimensions. In other words, the degree of lingual tipping of the first molar increased in the early phase, and decreased after the second peak. The greatest degree of lingual tipping was observed with the 0.017 × 0.025-in (2.4°) followed by the 0.018 × 0.025-in (1.0°), and bucco-linguial tipping was not observed with the 0.019 × 0.025-in at the completion of space closure. Similar results were found regarding the second molar (Figure 8).

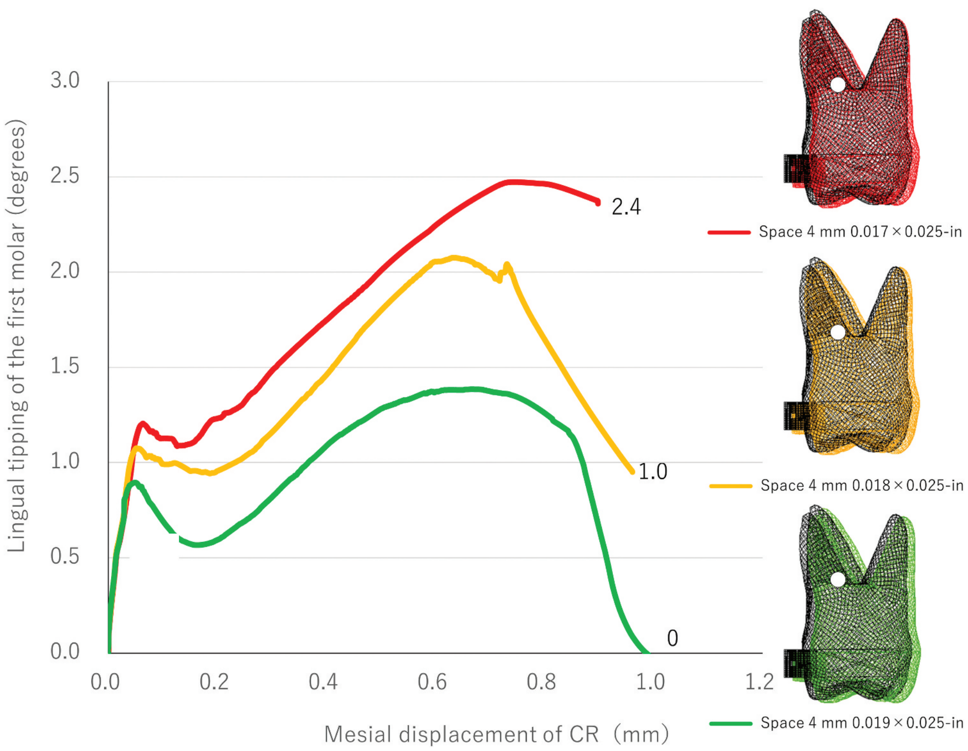


**Figure 8.** Degree of lingual tipping as a function of translational displacement at CR of the first molar in the mesial direction when the residual extraction space was 4 mm.

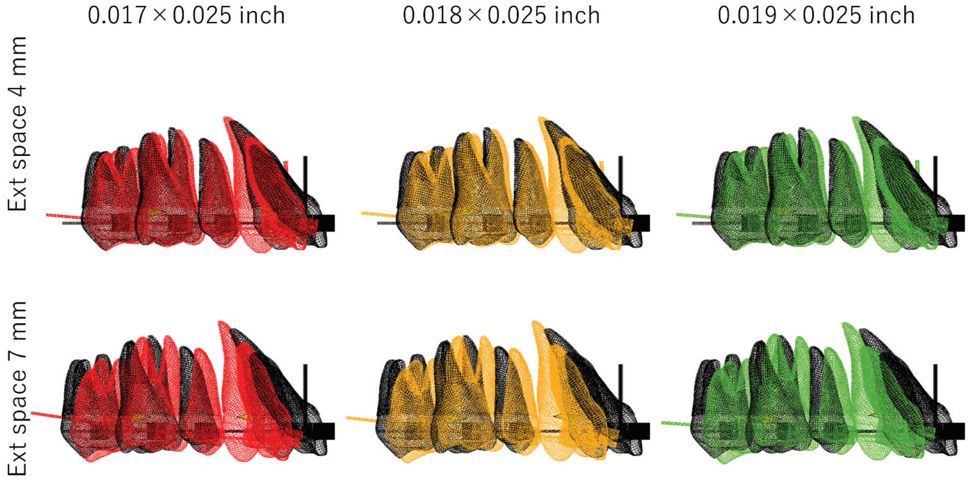


**Figure 9.** Schematic of superimposition before and after space closure for each group. Black is the initial position, red, orange, and green are the schema after space closure.

**Table 1.** Degree of rotation of the occlusal plane and the number of bone remodelling steps.

| | 0.017 × 0.25-in | 0.018 × 0.25-in | 0.019 × 0.25-in |
|---|---|---|---|
| Clock rotation of occlusal plane (degrees) | 0.6 | 0.7 | 0.4 |
| Number of bone remodelling steps (times) | 476 | 712 | 933 |

### *Rotation of the occlusal plane and velocity of space closure*

Table 1 shows the degree of rotation of the occlusal plane and the number of bone remodelling steps, which indicates the treatment duration required to close the extraction space of 4 mm. The occlusal plane rotated clockwise in all cases. The 0.018 × 0.025-in archwire produced the highest degree of clockwise rotation (0.7°), while the 0.019 × 0.025-in produced the least clockwise rotation (0.4°), although the values were negligible. The number of bone remodelling steps was the largest with the 0.019 × 0.025-in archwire (933 steps), followed by the 0.018 × 0.025-in archwire (712 steps), and the smallest with the 0.017 × 0.025-in archwire (476 steps).

## Discussion

The central incisor showed lingual crown tipping regardless of the archwire dimensions, and the larger the archwire size, the less substantially the incisor tipped. This result was in agreement with findings of the previous studies [8,13,14,23]. Wu et al. [23] reported the archwire size substantially affected the degree of labio-lingual tipping of the anterior teeth. An advantage of using an archwire with a larger cross-section such as 0.019 × 0.025-in archwire is the smaller play between the bracket slots and the archwire. This contributes to reducing the anterior torque loss, and thereby decreasing the degree of lingual crown tipping of the incisors. Tominaga et al. [12,16] also suggested that a smaller play between the brackets and the archwire might contribute to a more efficient torque application. On the contrary, 0.017 × 0.025-in or 0.018 × 0.025-in archwire may be less capable of controlling the movement of the anterior teeth because of the greater play between the brackets and the archwire.

The present study also suggested that the width of the residual extraction space after levelling has a significant impact on the amount of the tipping tendency of the central incisor. When the extraction space was set as 4 mm, the central incisor continued to increase in the degree of lingual crown tipping all through the space closure with the 0.017 × 0.025-in and 0.018 × 0.025-in archwire. However, with the 0.019 × 0.025-in archwire, the rate of increment of lingual crown tipping decreased in the latter phase of space closure. This could be attributed to the occurrence of third-order binding between the archwire and incisor bracket. Since the play between the bracket and 0.019 × 0.025-in archwire was smaller, the binding, wherein the diagonal corners of cross-section of the archwire came into contact with the bracket slot (Figure 3), occurred. Then, lingual root or anti-tipping moment was generated, and consequently the degree of lingual crown tipping stopped increasing during space closure when using the 0.019 × 0.025-in archwire. On the other hand, due to a larger play, no binding occurred all through the space closure; therefore, anti-tipping moment was not effectively delivered to the incisor bracket with the 0.017 × 0.025-in or the 0.018 × 0.025-in archwire. For this reason, it was considered that the central incisor showed a continuous increase in the tipping tendency until the completion of space closure, and the dimensions of 0.017 × 0.025-in and 0.018 × 0.025-in made only a small difference in the degree of lingual crown tipping.

When the extraction space was set as 7 mm, presuming that the anterior discrepancy was small, the degree of lingual crown tipping of the central incisor increased in the early phase of space closure. Then, third-order binding occurred in the middle phase of space closure for all archwire dimensions as seen in Figure 4. After the binding, the increment rate for incisor tipping decreased, since anti-tipping moment was produced. The larger the archwire dimension, namely, the smaller the play between the archwire and bracket, the earlier the binding occurred. As a result, the use of 0.019 × 0.025-in archwire could reduce the degree of lingual crown tipping of the central incisor the most, and 9.0 degree of tipping was produced at the completion of space closure. On the other hand, the use of 0.017 × 0.025-in and 0.018 × 0.025-in archwire generated a substantial degree of lingual crown tipping of 16.0 and 13.0, respectively.

Thus, this study showed that the movement or tipping trend for the incisor during space closure differed markedly between 4 and 7 mm of extraction space width. As the incisor tipped, the force system altered, and the rate of tipping movement also changed along the time axis, depending on the width of extraction space. In the present study, we found that the wider the extraction space, the more substantially the central incisor tipped lingually, since the degree of tipping is accumulating in the course of space closure depending on its width.

If the residual extraction space is less than 4 mm after levelling, controlled tipping of the central incisor could be achieved with the 0.019 × 0.025-in archwire in combination with 4 mm power arm (Figure 5). If lingual crown tipping more than 8 degrees is not desirable, the placement of longer power arm is recommended. If lingual crown tipping of 10 degrees is indicated, 0.018 × 0.025-in archwire can also be used, but 0.017 × 0.025-in archwire is not recommended, since the root apex cannot be moved lingually even with attaching 4 mm power arm onto the archwire. If the residual extraction space is 5–7 mm (in case of a small discrepancy in the anterior region), 0.019 × 0.025-in archwire must be used in combination with longer power arm unless the patient has severely proclined incisors.

To our knowledge, there has been no previous study that focused on the canine movement in en-masse retraction. Kojima et al. [24] evaluated the movement of the anterior segment as one unit. Our results were relatively close when it comes to distal tipping with a slight increase when using the 0.017 × 0.025-in archwire in case of 4 mm extraction space. The canine was distally displaced by 2.2 mm on average and the difference was not clinically significant between all archwires. These results appear to be more significant when the extraction space increased to 7 mm. In fact, the canine tipped distally more substantially when the 0.017 × 0.025-in archwire was used (11.8°) compared to the 0.019 × 0.025-in (7.1°).

The distal tipping of the canine was suppressed when using the 0.019 × 0.025-in after the canine was displaced distally by 3 mm, and then bodily movement occurred. This may be attributed to the occurrence of second order binding between the archwire and canine bracket. It was suggested that the larger the archwire dimension, the less substantially the canine tipped distally while using the 0.019 × 0.025-in archwire.

The first molar tipped mesially in the early phase of space closure, and then direction of tipping was changed from mesial to distal when the amount of mesial displacement exceeded 0.1 mm for all archwire dimensions. The first molar showed distal tipping at the completion of space closure, and there was no significant difference in the tipping degree among the three archwire sizes. According to previous studies [20,25,26], the reaction force acting on the molar has a vertical component in the intrusive direction when using power arm. Consequently, the distal end of the archwire was raised upward, which would cause the first molar to tip distally.

Komaki et al. [22] have also reported that the first molar showed lingual tipping during space closure in sliding mechanics. The present study indicated that the smaller the archwire dimension, the more substantially the molar would tip lingually. On the other hand, the use of the 0.019 × 0.025-in archwire would never tip the first molar in the bucco-lingual direction due to the smaller play between the tube and archwire with higher rigidity.

The finite element model, into which an algorithm of the bone remodelling process was incorporated, was used in this study [20,21,27]. Therefore, the number of bone remodelling steps is considered to represent treatment duration. It was found that the extraction space was closed faster using the 0.017 × 0.025-in (486 steps) compared to 0.019 × 0.025-in (943 steps). The larger the archwire dimension, the longer the space closure would take. The reason behind the difference in the velocity of space closure found among the three archwire sizes is mostly due to friction [24–28]. The larger the archwire dimension, the more friction will be generated upon sliding and the more time it will take to close the extraction space.

The PDL was modelled using a variety of methods, including linear-elastic, viscoelastic, hyperelastic, and multiphase methods [29]. Researchers have been unable to establish the correct hypothesis that precisely simulates the function of the PDL due to a paucity of experimental investigations and a lack of contemporary technologies to test the properties of the oral tissues. Our work used an isotropic and homogenous material property for the PDL in keeping with the bulk of dental finite element analysis studies, which could result in results that are oversimplified and erroneous.

The power arm used in this study had a fixed height of 4 mm and was soldered between the bracket of the lateral incisor and the canine. Many studies investigated the importance of the height of the power arm on one hand, and its position on the archwire on another hand [30,31]. If a different power arm length was used in our study, perhaps the results would have been different, and it would be interesting to investigate the consequent effects of that change. The distance to CR from bracket level for the central incisor was 7.1 mm [16]. With a 4 mm power arm, the line of force action did not pass through the centre of resistance of the central incisor, resulting in a bowing effect.

This study focused mainly on the changes observed in the maxillary dentition without taking into consideration the mandibular dentition nor the impact of the facial skeletal pattern which might have had an impact on the extraction space closure. This factor should be incorporated into the future finite element model to shed light on its clinical importance.

In addition, the difference in tooth movement velocity due to the difference in bone density between cortical and cancellous bone has not been considered. Moreover, further clinical studies are needed to validate the findings of our study.

## Conclusions

(1) The central incisor showed lingual crown tipping for all archwire dimensions even if the retraction force was applied from 4 mm power arm. The larger the archwire dimension, namely, the smaller the play between the archwire and brackets, the better torque control of the incisor could be achieved.
(2) The wider the residual extraction space, the more substantially the central incisor tipped lingually.
(3) The first molar showed lingual tipping when using archwires with smaller cross-section. The use of $0.019 \times 0.025$-in archwire could prevent the first molar from tipping in the bucco-lingual direction
(4) Although the use of large size archwires is recommended to provide the better controlled tooth movement and longer treatment duration is required.

## Authors contribution

- Dr Patrick El Saygh: Main investigator, data collection, analysis, writing and editing.
- Dr Runa Yamagushi : Data curation
- Dr Roland Kmeid: Co-investigator, advisor, co-director of the project.
- Dr Nabil Ghosn: Advisor, 3D model preparation.
- Dr Hiroya Komaki: Data curation, analysis, and review
- Dr Ryo Hamanaka: Data curation, analysis, and review
- Dr Noriaki Yoshida: Co-investigator, Finite element processing, and review.
- Pr. Joseph Bouserhal: Co-investigator, advisor, director of the project

## Author contributions

CRediT: **Patrick El Sayegh:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing; **Runa Yamagushi:** Data curation; **Roland Kmeid:** Supervision, Validation; **Nabil Ghosn:** Software; **Hiroya Komaki:** Investigation; **Ryo Hamanuka:** Data curation; **Noriaki Yoshida:** Data curation, Methodology; **Joseph Bouserhal:** Project administration.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

The author(s) reported there is no funding associated with the work featured in this article.

## Ethical approval

The study was approved by the Saint Joseph University Institutional Review Board under the code: USJ-2021-219.

## List of abbreviations

| | |
|---|---|
| 3D. | 3-dimensional |
| DICOM. | Digital imaging and communication in medicine |
| PDL. | Periodontal ligament |
| CR. | Center of resistance |

## References

[1] Proffit WR, Fields HW, Larson B, et al Fourth edition. Contemporary orthodontics-e-book. Elsevier Health Sci. 2018 3.
[2] Barlow M, Kula K. Factors influencing efficiency of sliding mechanics to close extraction space: a systematic review. Orthod Craniofacial Res. 2008;11 (2):65–73. doi: 10.1111/j.1601-6343.2008.00421.x
[3] Iwasaki LR, Haack JE, Nickel JC, et al. Human tooth movement in response to continuous stress of low magnitude. Am J Orthod Dentofacial Orthop. 2000;117(2):175–183. doi: 10.1016/S0889-5406(00)70229-0

[4] Kuhlberg AJ, Burstone CJ. T-loop position and anchorage control. Am J Orthod Dentofacial Orthop. 1997;112(1):12–18. doi: 10.1016/S0889-5406(97)70268-3

[5] Burstone CJ, Koenig HA. Force systems from an ideal arch. Am J Orthod. 1974;65(3):270–289. doi: 10.1016/S0002-9416(74)90332-7

[6] Azevedo ÁF. Método dos elementos finitos. Faculdade de Engenharia da Universidade Do Porto. 2003;1(7):3–4

[7] Bourauel C, Vollmer D, Jäger A. Application of bone remodeling theories in the simulation of orthodontic tooth movements. J Orofac Orthopedics / Fortschr der Kieferorthopädie. 2000;61(4):266–279. doi: 10.1007/s560050012

[8] Bourauel C, Freudenreich D, Vollmer D, et al. Simulation of orthodontic tooth movements. A comparison of numerical models. J Orofac Orthop. 1999;60(2):136–151. doi: 10.1007/BF98963

[9] Schneider J, Geiger M, Sander FG. Numerical experiments on long-time orthodontic tooth movement. Am J Orthod Dentofacial Orthop. 2002;121(3):257–265. doi: 10.1067/mod.2002.11007

[10] Nguyen AT, Hamanaka R, Jinnai S, et al. Simulation of orthodontic tooth movement during activation of an innovative design of closing loop using the finite element method. Am J Orthod Dentofacial Orthop. 2021;160(2):240–249. doi: 10.1016/j.ajodo.2020.04.026

[11] Middleton J, Jones M, Wilson A. The role of the periodontal ligament in bone modeling: the initial development of a time-dependent finite element model. Am J Orthod Dentofacial Orthop. 1996;109(2):155–162. doi: 10.1016/S0889-5406(96)70176-2

[12] Tominaga JY, Ozaki H, Chiang PC, et al. Effect of bracket slot and archwire dimensions on anterior tooth movement during space closure in sliding mechanics: a 3-dimensional finite element study. Am J Orthod Dentofacial Orthop. 2014;146(2):166–174. doi: 10.1016/j.ajodo.2014.04.016

[13] Kojima Y, Fukui H. Numerical simulation of canine retraction by sliding mechanics. Am J Orthod Dentofacial Orthop. 2005;127(5):542–551. doi: 10.1016/j.ajodo.2004.12.007

[14] Kojima Y, Fukui H. Numeric simulations of en-masse space closure with sliding mechanics. Am J Orthod Dentofacial Orthop. 2010;138(6):702–e1. doi: 10.1016/j.ajodo.2010.08.005

[15] Tominaga JY, Tanaka M, Koga Y, et al. Optimal loading conditions for controlled movement of anterior teeth in sliding mechanics: a 3D finite element study. Angle Orthod. 2009;79(6):1102–1107. doi: 10.2319/11608-587R.1

[16] Hamanaka R, Yamaoka S, Anh TN, et al. Numeric simulation model for long-term orthodontic tooth movement with contact boundary conditions using the finite element method. Am J Orthod Dentofacial Orthop. 2017;152(5):601–612. doi: 10.1016/j.ajodo.2017.03.021

[17] Jinnai S, Hamanaka R, Komaki H, et al. Mesial or distal to canine: which is better for the position of closing loops? Analysis of tooth movements based on numerical simulation. Am J Of Orthod Dentofac Orthop. 2023;163(5):645–655. doi: 10.1016/j.ajodo.2022.04.018

[18] Barsoum HA, ElSayed HS, El Sharaby FA, et al. Comprehensive comparison of canine retraction using NiTi closed coil springs vs elastomeric chains: a split-mouth randomized controlled trial. Angle Orthod. 2021;91(4):441–448. doi: 10.2319/10620-916.1

[19] Sia SS, Koga Y, Yoshida N. Determining the center of resistance of maxillary anterior teeth subjected to retraction forces in sliding mechanics: an in vivo study. Angle Orthod. 2007;77(6):999–1003. doi: 10.2319/12206-478

[20] Collidge ED. The thickness of the human periodontal membrane. J Am Dent Assoc Dent Cosmos. 1937;24(8):1260–1270. doi: 10.14219/jada.archive.1937.0229

[21] Reimann S, Keilig L, Jager A, et al. Biomechanical finite-element investigation of the position of the centre of resistance of the upper incisors. Eur J Orthod. 2007;29(3):219–224. doi: 10.1093/ejo/cjl086

[22] Komaki H, Hamanaka R, Tominaga JY, et al. Biomechanical features of tooth movement from a lingual appliance in comparison with a labial appliance during space closure in sliding mechanics. Am J Orthod Dentofacial Orthop. 2022;162(3):307–317. doi: 10.1016/j.ajodo.2021.03.024

[23] Wu J, Wang X, Jiang Y, et al. Effect of archwire plane and archwire size on anterior teeth movement in sliding mechanics in customized labial orthodontics: a 3D finite element study. BMC Oral Health. 2022 10;22(1):33. doi: 10.1186/s2903-022-02066-9

[24] Kojima Y, Fukui H, Miyajima K. The effects of friction and flexural rigidity of the archwire on canine movement in sliding mechanics: a numerical simulation with a 3-dimensional finite element method. Am J Orthod Dentofacial Orthop. 2006;130(3):275–e1. doi: 10.1016/j.ajodo.2006.02.030

[25] Kusy RP, Whitley JQ. Friction between different wire-bracket configurations and materials. Semin Orthod. 1997;3(3):166–177. doi: 10.1016/S1073-8746(97)80067-9

[26] Kusy RP, Whitley JQ, Prewitt MJ. Comparison of the frictional coefficients for selected archwire-bracket slot combinations in the dry and wet states. Angle Orthod. 1991;61(4):293–302. doi: 10.1043/0003-3219(1991)061<0293:COTFCF>2.0.CO;2

[27] Nattrass C, Ireland AJ, Sherriff M. An investigation into the placement of force delivery systems and the initial forces applied by clinicians during space closure. Br J Orthod. 1997;24(2):127–131. doi: 10.1093/ortho/24.2.127

[28] Kojima Y, Kawamura J, Fukui H. Finite element analysis of the effect of force directions on tooth movement in extraction space closure with miniscrew sliding mechanics. Am J Orthod Dentofacial Orthop. 2012;142(4):501–508. doi: 10.1016/j.ajodo.2012.05.014

[29] Fill TS, Toogood RW, Major PW, et al. Analytically determined mechanical properties of, and models for the periodontal ligament: critical review of literature. J Biomech. 2012 Jan 3;45(1):9–16. doi: 10.1016/j.jbiomech.2011.09.020

[30] Ahmed N, Megalan P, Suryavanshi S, et al. Effect of bracket slot and archwire dimension on posterior tooth movement in sliding mechanics: a three-dimensional finite element analysis. Cureus. 2019;11(9). doi: 10.7759/cureus.5756

[31] El Khoury T, Karam R, Dib E, et al. Three-dimensional comparison of the effects of sliding mechanics in labial and lingual orthodontics using the finite element method. Am J Orthod Dentofacial Orthop. 2022;162(1):24–32. doi: 10.1016/j.ajodo.2021.02.019