Biomechanical analysis for total distalization of the mandibular dentition: A finite element study

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Introduction: The aim of this finite element study was to analyze and clarify the mechanics of tooth movement patterns for total distalization of the mandibular dentition based on force angulation. **Methods:** Long-term orthodontic movement of the mandibular dentition was simulated by accumulating the initial displacement of teeth produced by elastic deformation of the periodontal ligament. **Results:** Displacement of each tooth was caused by movement of the whole dentition, elastic deflection of the archwire, and clearance gap between the archwire and bracket slot. The whole dentition was rotated clockwise or counterclockwise when the line of action of the force passed below or above the center of resistance. Elastic deflection of the archwire induced a lingual tipping of the anterior teeth. It became larger when increasing the magnitude of angulation. The archwire could be rotated within the clearance gap between the archwire and the bracket slot, and thereby the teeth tipped. **Conclusions:** Mechanics of total mandibular distalization was clarified. Selective use of force angulation with a careful biomechanical understanding can achieve proper distalization of the whole mandibular dentition. (Am J Orthod Dentofacial Orthop 2019;155:388-97)

Class III malocclusion is the most common skeletal malocclusion, and mandibular prognathism is one of the most prevalent complaints for Asian orthodontic patients.[1] Class III treatment is a considerable clinical challenge and commonly includes growth modification involving a chincup to restrain mandibular growth or a facemask to protract the maxilla, dentoalveolar compensation or camouflage involving dental extractions, or orthognathic surgery.[2]

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In growing Class III patients, upward-and-forward rotation of the mandible in combination with forward growth is highly associated with unsatisfactory treatment outcomes after pubertal growth.[3] Surgical repositioning of the maxilla and/or mandible is often required when treating severe Class III adult patients. Mild-to-moderate Class III patients can be treated nonsurgically, but proper diagnosis and realistic treatment objectives are necessary to prevent undesirable sequelae.[4-7]

The choice between camouflage treatment and orthognathic surgery remains a challenge to clinicians. Class III patients who decline orthognathic surgery have been treated with conventional fixed orthodontic appliances along with mandibular cervical headgear, mandibular high-pull J-hook headgear, Class III elastics, extractions, and multiloop edgewise archwire therapy.[8-16] Clinicians have attempted to treat Class III malocclusion by various methods of distalization of the mandibular dentition. Although distalization of the molars has been one of the most difficult biomechanical problems in traditional orthodontics, particularly in adults, it has now become possible to distalize mandibular molars with the use of various temporary skeletal anchorage devices (TSADs).[8,17-30]

In the treatment of adult mild-to-moderate Class III malocclusions, TSADs are quite useful compared with traditional orthodontic mechanics because they allow for

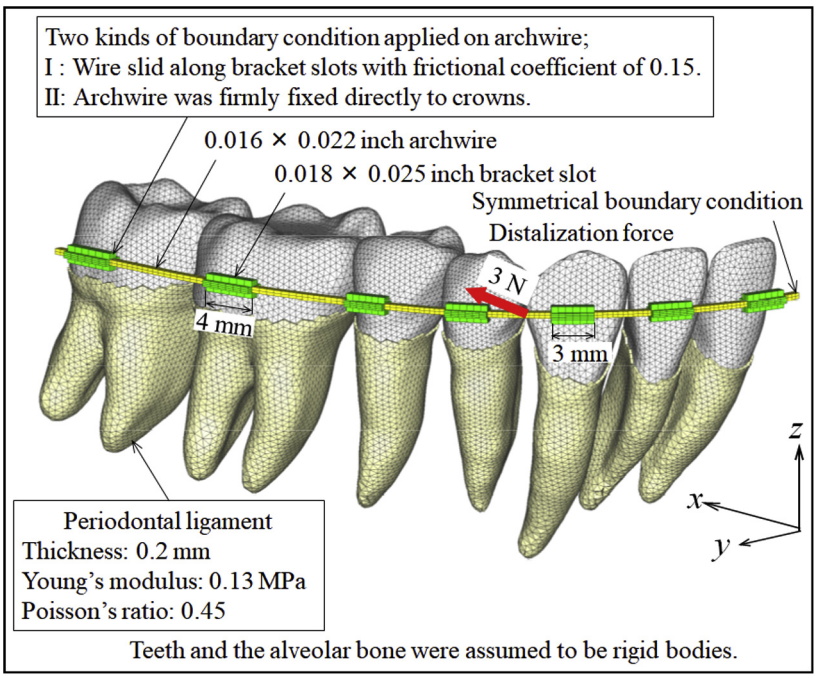

Fig 1. Finite element model for simulating orthodontic tooth movement.

whole-arch distalization of the mandibular dentition without any anchorage loss or the need for patient cooperation. Careful use of TSADs together with an understanding of the biomechanical principals involved can expand the boundaries and scope of conventional fixed appliance therapy. Several biomechanical strategies[8-30] have been attempted to correct Class III malocclusions when there are severe skeletal and dental variations, but there have been few studies about biomechanical consideration for distalization of the mandibular dentition.

The aim of the present study was to analyze and clarify the mechanics of distalizing tooth movement patterns of the mandibular dentition according to the force angulation.

MATERIAL AND METHODS

Figure 1 shows the finite element model (FEM) for simulating orthodontic tooth movement. Assuming bilateral symmetry of the mandibular dentition, only the right side was modeled. Three-dimensional models of the teeth were made based on computerized tomographic images of a dental study model (i21D-400C; Nissin Dental Products, Kyoto, Japan).[31] Each tooth was meshed with shell elements and defined as a rigid body.

The teeth and the alveolar bone were assumed to be rigid bodies. The periodontal ligament (PDL) was assumed to be a linear elastic material with uniform thickness of 0.2 mm, whose Young modulus and Poisson ratio were 0.13 MPa and 0.45, respectively.[31]

The archwire was made of 0.016 × 0.022-inch stainless steel (SS) wires whose Young modulus and Poisson ratio were 200 GPa and 0.3, respectively, and the symmetric boundary condition was applied at the median end of the archwire. Brackets of 0.018 × 0.025-inch slot were bonded on the crowns. The width of the bracket was 4 mm for the molars and 3 mm for the other teeth. The brackets were meshed with shell elements and defined as rigid bodies.

Two different kinds of boundary conditions were assumed between the archwire and the teeth. In the first boundary condition, which included the clearance gap (play) between the archwire and the bracket slot, the archwire slid along the bracket slot whose frictional coefficient was assumed to be 0.15.[32] Figure 2 shows the initial and contact positions of the archwire in the bracket slot. Until it made contact, the archwire could rotate by 4.7° in the clearance gap. The archwire was divided into quadratic hexahedron elements on which contact elements were set against the bracket slots. Contact elements were also set on the crown surface to prevent penetration between adjacent teeth. In the second boundary condition, excluding the effect of clearance gap, the archwire was firmly fixed directly to the crowns. Contact elements between the archwire and bracket slot became unnecessary, and the archwire could be divided

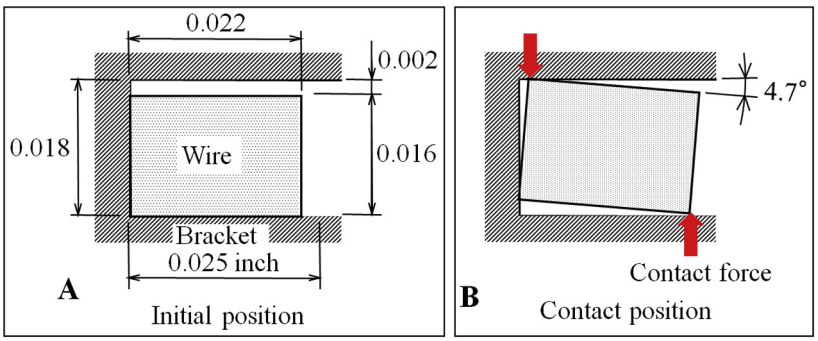

Fig 2. Initial and contact positions of the archwire put into the bracket. The archwire can rotate by 4.7° within the clearance gap.

into the beam elements. Because the teeth did not move along the archwire, contact elements were not set on the crown surface.

Because each tooth moves individually by an elastic deformation of the archwire, the center of resistance (CR) of the whole dentition can not be determined.[33] Therefore, the CR was determined with the use of a rigid archwire with an extremely large Young modulus, 200×10^3 GPa.[34] The rigid archwire moved the whole dentition as 1 united body. The location of the CR could be strictly defined because of the bilateral symmetry of the mandibular dentition.[35]

Forces were applied on the wire between the canine and first premolar brackets at −30°, −15°, 0°, 15°, and 30° to the occlusal plane. Negative values of force angulation mean that the line of action of the force is in a posteroinferior direction along the occlusal plane, and positive values mean the opposite. The magnitude of the force in *x*-*z* plane was 3 N, and the *y*-component of the force was 0. This amount of force was the same as with some clinical cases.[9,21,25] Four points were selected, which included the central incisal edge (CIE), mesiobuccal and distobuccal cusps of first molar (MBC6 and DBC6), and distobuccal cusp of second molar (DBC7), for evaluation of each tooth displacement, buccolingual and mesiodistal angulation, and occlusal plane angle. The results of displacement were each expressed in *x*, *y*, and *z* axes, which were the directions of the anterior-posterior, transverse, and vertical movements, respectively. The positive values of the *x*, *y*, and *z* axes mean: posterior, left, upward movement; buccal and mesial tipping; and clockwise rotation of the occlusal plane angle.

Orthodontic movement was assumed to occur by accumulating the initial displacement of teeth produced by elastic deformation of the PDL.[36] First, the initial displacement was calculated, and then the alveolar socket of each tooth was moved by the same amount as the initial displacement. By repeating this calculation, the teeth moved step by step. The force system acting on the teeth was updated at each step. Number of the steps, *N*, corresponds to the time elapsed after the force application. For the finite element simulation, Ansys 11 (Canonsburg, Pa) was used.

RESULTS

Figure 3 shows the CR of the whole mandibular dentition, which was determined with the use of the rigid archwire. At a force angulation of −23°, the line of action of the force passed through the CR.

Figure 4 shows the movement patterns of the mandibular dentition at n = 500 when applying horizontal forces. Initial tooth positions are drawn in a pale shade. Distribution of mean stress or the hydrostatic stress in the PDL is drawn on the roots with colored contours. Red and blue indicate compressive and tensile stresses, respectively. Blue lines drawn on the archwire indicate approximate inclinations or the rotation angle of the whole dentition.

Figure 4 also shows the effect of clearance gap between the archwire and the bracket slot. In the case where the brackets slid along the archwire with a clearance gap (Fig 4, *A*), lingual tipping angles of the central incisor and the molar were 14.2° and 4.7°, respectively. In the case where the archwire was firmly fixed directly to the crowns (Fig 4, *B*), lingual tipping angles of the central incisor and the molar were 10.5° and 0.8°, respectively. The differences in the tipping angles between Figure 4, *A* and *B* were 14.2° − 10.5° = 3.7° (incisor) and 4.7° − 0.8° = 3.9° (molar), which were roughly equal to the rotation angle of the archwire in the bracket slot: 4.7° (Fig 2, *B*). Rotation angles of the whole dentition were approximately −5° (Fig 4, *A*) and −4° (Fig 4, *B*). Their difference was 1°, that is, both movement patterns of the whole dentition were almost the same.

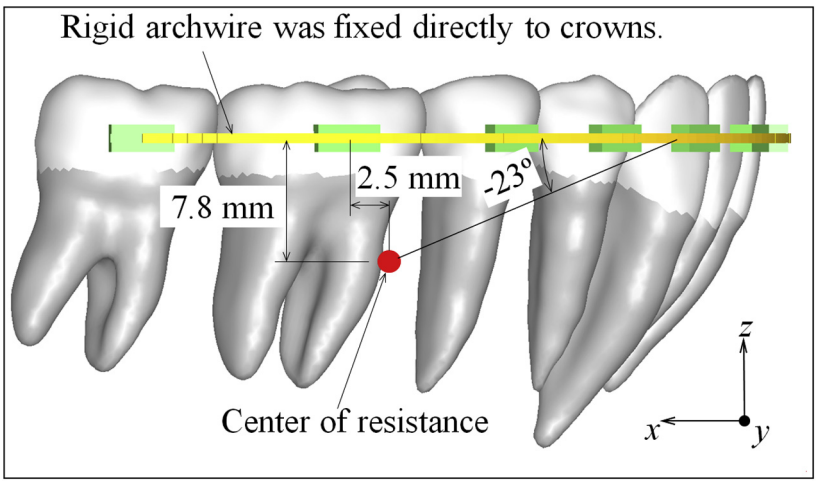

Fig 3. Location of the center of resistance (CR) of the whole dentition as determined with the use of a rigid archwire. At a force angulation of −23°, the line of action of the force passes through the CR.

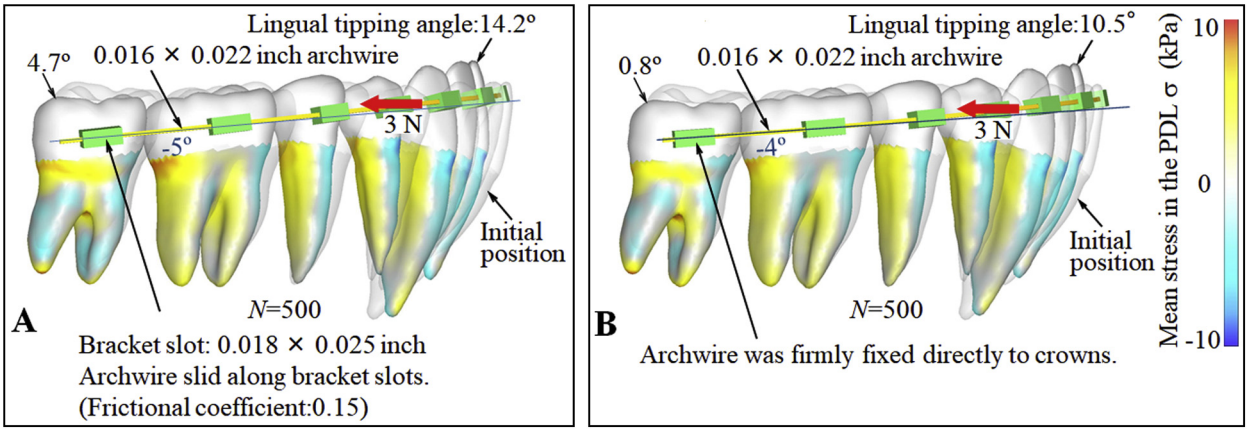

Fig 4. Tooth movement patterns at $N = 500$ when applying a horizontal force. Contact elements are set on the crowns. **A,** The archwire slides along the bracket slots with a frictional coefficient of 0.15. **B,** The archwire is firmly fixed directly to the crowns.

In the case of Figure 4, *B*, the necessity of contact elements on the crown surface was examined. When the contact elements were not set on the crowns, penetrations of the adjacent crowns occurred but the amounts were within 0.1 mm. Owing to these penetrations, the tipping angle of the central incisor was increased by 0.2°.

Figure 5 shows the movement patterns of the mandibular dentition at n = 500 when distalization force was applied from −30° to 30° to the occlusal plane with the rigid or the elastic archwire that was firmly fixed directly to the crowns. Because movement patterns in the occlusal view were almost the same in all cases, only a case of −30° force angulation is shown. Table presents 3-dimensional displacements and rotation of the incisor and molars.

The blue lines in Figure 5 indicate approximate inclinations of the whole dentition in the case of rigid archwires whose elastic deflections were negligible. With the elastic archwires, their deviation from the blue lines indicates the amount of elastic deflection of the archwire. The elastic deflection was increased by force angulation and increased the lingual tipping of the anterior teeth.

With the rigid archwire, the whole dentition moved as 1 united body. This movement pattern was dependent only on the line of action of the force in relation to the CR of the whole dentition, not on the amount of force. At a force angulation of −30° (Fig 5, *A*), the line of action of the force passed below the CR, and thereby the whole dentition rotated clockwise. When a force angulation was larger than −23°, the line of action

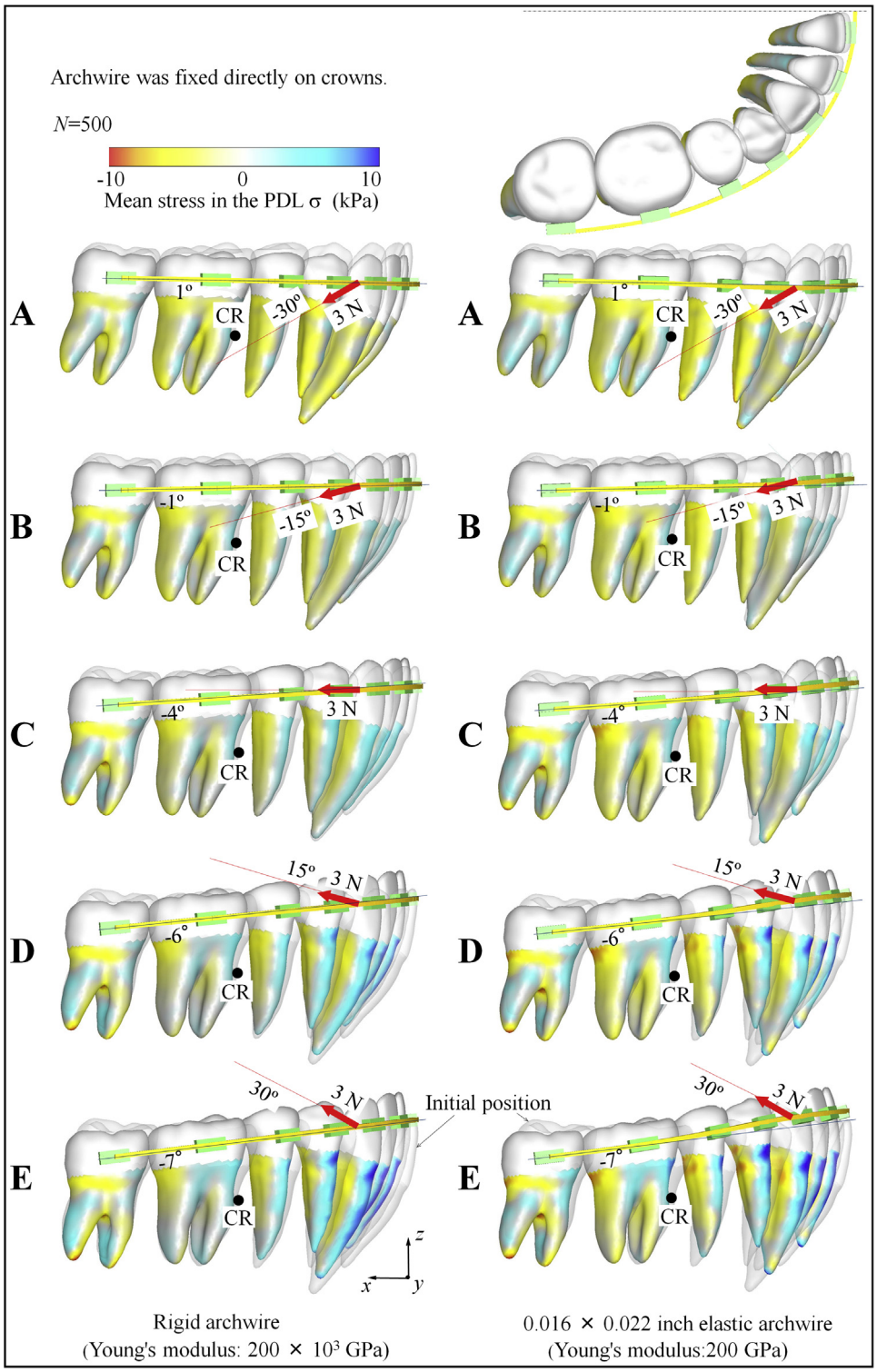

Fig 5. Tooth movement patterns at $N = 500$ for 5 force angulations to the occlusal plane: **A,** −30°; **B,** −15°; **C,** 0°; **D,** 15°; **E,** 30°. Left and right figures are in the case of rigid and 0.016 × 0.022 inch elastic archwires, respectively. Difference between left and right movement patterns is due to elastic deflection of the archwire. Right upper figure is a typical movement pattern in occlusal view.

Table. Three-dimensional displacements and rotation of the incisor and the molars

	Force angulation									
	Rigid archwire					*0.016 × 0.022-inch stainless steel archwire*				
Measurement point	*−30°*	*−15°*	*0°*	*15°*	*30°*	*−30°*	*−15°*	*0°*	*15°*	*30°*
CIE										
x (mm)	0.53	0.97	1.39	1.75	2.00	0.69	1.50	2.21	2.73	3.03
y (mm)	0.00	0.00	0.00	0.00	0.00	−0.03	0.01	0.05	0.08	0.09
z (mm)	−1.70	−0.29	1.13	2.43	3.52	−1.60	0.22	1.88	3.30	4.40
BLA (°)	1.19	−1.20	−3.49	−5.48	−7.04	0.94	−5.29	−10.46	−14.32	−16.80
MDA (°)	0.00	0.00	0.00	0.00	−0.01	−0.43	0.07	0.48	0.80	1.03
MBC6										
x (mm)	0.54	0.95	1.30	1.57	1.73	0.38	1.11	1.75	2.24	2.56
y (mm)	0.00	0.00	0.00	0.00	0.00	−0.55	−0.41	−0.23	−0.03	0.17
z (mm)	−1.24	−0.75	−0.21	0.33	0.84	−1.21	−0.62	−0.04	0.49	0.96
BLA (°)	0.01	0.00	−0.01	−0.02	−0.02	2.86	1.61	0.33	−0.91	−2.05
MDA (°)	1.19	−1.19	−3.46	−5.44	−6.99	1.91	−1.68	−4.95	−7.64	−9.61
DBC6										
x (mm)	0.53	0.95	1.31	1.58	1.74	0.36	1.12	1.77	2.25	2.56
y (mm)	0.00	0.00	0.00	0.00	0.00	−0.56	−0.40	−0.22	−0.02	0.17
z (mm)	−1.11	−0.87	−0.59	−0.26	0.08	−1.09	−0.84	−0.59	−0.32	−0.03
BLA (°)	0.01	0.00	−0.01	−0.02	−0.02	2.86	1.61	0.33	−0.91	−2.05
MDA (°)	1.19	−1.19	−3.46	−5.44	−6.99	1.91	−1.68	−4.95	−7.64	−9.61
DBC7										
x (mm)	0.52	0.96	1.31	1.56	1.69	0.36	1.05	1.61	2.02	2.26
y (mm)	0.00	0.00	0.00	0.00	0.00	−0.46	−0.29	−0.11	0.06	0.24
z (mm)	−0.82	−1.17	−1.44	−1.60	−1.64	−0.73	−1.09	−1.39	−1.57	−1.63
BLA (°)	0.01	0.00	−0.01	−0.03	−0.03	2.99	2.24	1.36	0.39	−0.64
MDA (°)	1.19	−1.19	−3.46	−5.54	−7.00	0.75	−1.73	−3.95	−5.75	−7.05
OPA	1.19	−1.19	−3.46	−5.45	−6.99	1.18	−1.79	−4.47	−6.66	−8.24

Rigid archwire: wire with no elastic deflection made by increasing Young modulus of 0.016 × 0.022-inch archwire by a thousand times ($E = 200 \times 10^3$ GPa). Measurement points: *CIE*, central incisal edge; *MBC6*, mesiobuccal cusp of first molar; *DBC6*, distobuccal cusp of first molar; *DBC7*, distobuccal cusp of second molar. Three-dimensional axes: *x*, posterior (+) and anterior (−); *y*, left (+) and right (−); *z*, superior (+) and inferior (−). Angulations: *BLA*, buccolingual angulation, buccal (+) and lingual (−); *MDA*, mesiodistal angulation, mesial (+) and distal (−); *OPA*, occlusal plane angle, clockwise (+) and counterclockwise (−).

of the force passed above the CR and the whole dentition rotated counterclockwise as shown in Figure 5, *B-E*. When increasing the force angulation, the line of action of the force moved away from the CR, and thereby counterclockwise moment on the CR was increased. As a result, rotation of the whole dentition was increased. At the same time, the magnitude of stress in the PDL was increased.

At force angulation of 0°, that is, the horizontal force, the posterior teeth intruded but the anterior teeth extruded without any vertical component of the force (Fig 5, *C*). When increasing the force angulation in a negative or positive direction, the downward or upward component of the force caused an intrusion or extrusion of the whole dentition (Fig 5, *A* and *E*).

DISCUSSION

The decision to treat a severe skeletal Class III malocclusion with the use of surgery or nonsurgical orthodontic approaches still lacks a clear consensus, but camouflage treatment is usually considered only for borderline patients. Conventional Class III camouflage treatment typically involves proclination of the maxillary incisors and retroclination of the mandibular incisors to improve the dental occlusion, but it might not correct the underlying skeletal problem or facial profile, and the treatment results depend on the patient's cooperation.[4,8]

TSADs, compared with conventional orthodontic mechanics, are quite useful in the treatment of adult mild-to-moderate Class III malocclusions because they allow for group distalization of the mandibular arch dentition without any anchorage loss or the need for patient cooperation.[26] Therefore, careful use of TSADs together with an understanding of the biomechanical principals involved can expand the boundaries and scope of conventional fixed appliance therapy.[27]

Distalization of the mandibular arch dentition can be achieved with the use of various biomechanical strategies according to force angulations to the occlusal plane.

In this study, we investigated the mechanics of distalizing tooth movement with the use of finite element analysis according to 5 force angulations relative to the occlusal plane, from −30° to 30°, which can be converted into clinical situations such as mandibular cervical headgear therapy (−30°),[9] mandibular TSADs and intra-arch elastics (−30° to 0°),[17-27,30] maxillary TSADs and Class III elastics (15° to 30°),[26-29] high-pull headgear or MEAW and Class III elastics (15° to 30°),[11,16,26,27,29] and mandibular high-pull J-hook headgear (30°).[10]

The CR position is important to the prediction of biomechanical tooth movement. In this study, distalization forces from −30° to 30° to the occlusal plane were applied on the wire between the mandibular canine and first premolar, and the force angulation of −23° passed through the CR of the whole mandibular dentition, which was consistent with an earlier study (Fig 3).[37] Therefore, the biomechanical tooth movement would be different depending on whether the force passed above, at, or below the CR and the degree of force angulation. On the other hand, distolingual moment on the posterior teeth would occur during distalization because of the buccolingual distance from the line of action of the force to the CR. But the amount of tooth movement at MBC6, DBC6, and DBC7 on the *y* axis was negligible, so a concern about distolingual rotation of the posterior teeth might not be necessary during distalization.

In this study, the amount of distalization increased as force angulation increased, except at DBC7, with the use of 0.016 × 0.022-inch SS archwire. With the force angulation of −30°, the amount of distalization was small, which would be the reason why this force angulation has not been used in a clinical situation. The amount of transverse movement also was small, so a concern about transverse tipping might not be necessary during distalization. The amount of vertical movement is critical because it can affect the treatment results significantly. CIE showed an extrusion in most situations except with the force angulation of −30°. The amount of extrusion was greatest at CIE and increased as force angulation increased, except at DBC7 where the amount of intrusion increased as force angulation increased. The amount of lingual tipping at CIE increased as force angulation increased, and lingual tipping at MBC6, DBC6, and DBC7 showed the same pattern but was smaller than it was at CIE. The amount of distalization, extrusion and lingual tipping was greater with the 0.016 × 0.022-inch SS archwire than with a rigid archwire, because of elastic deflection of the wire. The amount of mesiodistal tipping at CIE was almost zero. The amount of distal tipping at MBC6, DBC6, and DBC7 increased as force angulation increased. The occlusal plane angle became more counterclockwise as force angulation increased, but clockwise rotation occurred in the force angulation of −30°.

Therefore, the tooth movement pattern depends on archwire size, the magnitude of distalizing force, and force angulation. In clinical studies,[9-11,16-30] the authors usually have used 0.016 × 0.022, 0.017 × 0.025, and 0.019 × 0.025-inch SS archwires, 200, 250, 300, and 450 g of force, and various force angulations (−30° to 30°). In this study, we selected 0.016 × 0.022-inch SS and rigid archwires, 300 g of force, and 5 force angulations that would be similar to clinical situations.

The mandibular dentition was distalized without significant vertical movement with a simulation of the force angulation of −15°, and these results were similar to those of some earlier studies using TSADs.[17,24-27,30] This strategy can be used in the case where vertical variables such as Frankfort-mandibular plane angle, anterior facial height, and overbite need to be maintained. On the other hand, the mandibular dentition was distalized with lingual tipping and extrusion of the mandibular incisors, distal tipping and intrusion of the mandibular molars, and counterclockwise rotation of the occlusal plane in the simulation of the force angulation of 0°, 15°, and 30°. These results became greater as force angulation increased and were similar to those of some studies using TSADs, Class III elastics, and mandibular high-pull J-hook headgear.[10-16,18-23,28,29] These strategies can be used for patients with high angle and open bite tendency. Therefore, the choice of the biomechanical strategy should be dependent on the amount of 3-dimensional tooth displacement. This might explain the usefulness of FEM studies.

Although MBC6 was a bit extruded in the force angulation of 15° and 30°, this slight extrusion of the posterior dentition should not be of concern in patients with a brachyfacial growth pattern, but it could have severe consequences in dolichofacial patients.[23] Long-face individuals commonly display excessive eruption of the posterior teeth and have significantly less occlusal force.[38] Forces from occlusion have been reported to play a role in the vertical position of the teeth by affecting eruption.[39] Thus, despite the use of effective mechanics, it might be difficult to completely prevent molar extrusion in long-face individuals.[11] Therefore, when selecting specific treatment mechanics for distalization, the skeletal and facial growth patterns of patients should be carefully evaluated. This might be the limitation of FEM studies.

Segmental distalization of the mandibular posterior teeth was attempted in some studies[9,10,16-18,22,24,30] to attain the spaces for alignment and en masse retraction of the anterior teeth after total distalization of

the mandibular dentition. Biomechanical tooth movement pattern of segmental distalization would be different from the total distalization because the CR position would be different. Further study is necessary to identify the CR position of the segmental posterior teeth and clarify the mechanics of tooth movement patterns for segmental distalization of the mandibular posterior dentition according to the force angulation.

Available space in the posterior retromolar area should be analyzed before distalization of the mandibular dentition to prevent periodontal problems.[24,40] Mandibular headgear or Class III elastics can put upward and backward pressure on the mandible that should be reduced to prevent adverse effect on the temporomandibular joint.[5] And when retracting mandibular incisors, great care should be taken to reduce the risk of significant decreases in lingual bone width.[6] Lip paresthesia can occur during mandibular molar orthodontic distalization owing to excessive dimensions of the mandibular second molar roots, so there should be a detailed analysis of the panoramic radiograph to prevent nerve numbness and damage.[7]

The present study did not include curve of Spee, which is a naturally occurring phenomenon in the human dentition. In high-angle subjects, orthodontic leveling of the curve of Spee occurred through extrusion and uprighting of the mandibular posterior teeth.[41] A future study might be recommended to evaluate the effects of curve of Spee in relation to the amount of distalization and angulation.

The orthodontic tooth movement was predicted by means of the initial tooth movement produced by elastic deformation of the PDL. Both movement patterns were assumed to be similar to each other. This essential assumption is acceptable in clinical situations. In an in vivo animal experiment, there were indications that the initial displacement became a predictor of long-term orthodontic movement.[42] The validity of other assumptions, for example, the linear elastic property of the PDL, the rigid teeth, the rigid alveolar bone, and various forces acting on the dentition, were discussed in a previous article.[43]

The finite element simulation was able to clarify mechanical factors that influence the distalization of mandibular dentition. In such a cause-analysis investigation, the FEM has an advantage over clinical studies. The displacement of each tooth was caused by movement of the entire dentition, elastic deflection of the archwire, and clearance gap between archwire and bracket slot, but it was possible to investigate each element individually by changing the boundary conditions. The details are as follows.

Movement of the whole dentition was dependent only on the force direction in relation to the CR of the whole dentition. When the line of action of the force passed below or above the CR, the whole dentition was rotated clockwise or counterclockwise, respectively.

Elastic deflection of the archwire induced a lingual tipping of the anterior teeth. When the magnitude of angulation was increased, the elastic deflection became larger due to an increase in the bending moment acting on the archwire. The elastic deflection increased in proportion to the distalization force. If an archwire having low Young's modulus or small size was used, the elastic deflection would be increased.

The archwire could be rotated within the clearance gap between the archwire and the bracket slot, and thereby the teeth tipped. The amount of the tipping angle due to the clearance gap could easily be predicted by drawing a geometric figure of the archwire within the bracket slot (Fig 2, *B*). If a 0.016 × 0.022-inch archwire was put into 0.025 inch brackets, tipping due to the clearance gap would be increased to 15.0°. However this tipping would hardly affect the movement pattern of the whole dentition.

We should understand that tipping due to the clearance gap is remarkably affected by the initial placement of the archwire. In the initial placement where the upper surface of the wire is parallel to the bracket slot (Fig 2, *A*), the clearance gap is the largest and maximum tipping occurs. When the initial placement is made with the diagonal corners of cross-section of the archwire in contact with the bracket slot (Fig 2, *B*), tipping due to the clearance gap does not occur. This case is encountered when an archwire is placed into the bracket slots after leveling or alignment, or when the initial tooth angulation or bracket position deviate slightly from their normal positions. In clinical settings, the contact conditions are different in each individual bracket slot, but only an idealized case of the initial placement of the archwire was simulated. The results will still give clinicians the improper information. This is a limitation of the FEM.

Tipping due to the elastic deflection of the archwire can be prevented by using a prebent archwire or by torqueing. But for tipping due to the clearance gap, such compensations are not always valid. For the tipping of the incisors, when using a compensating archwire, the incisors must be uprighted themselves, but other teeth might also tip as a reaction.

In the case where the archwire slides along the bracket slots (Fig 4, *A*), after the teeth have moved distally to close interproximal spaces between them,

the dentition moves as 1 united body. This movement pattern is similar to that in Figure 4, *B*, where the archwire was firmly fixed directly to the crowns. In this boundary condition when contact elements were not set on the crowns, a slight penetration of adjacent teeth occurred but hardly changed the movement pattern of the dentition. This means that the contact elements are unnecessary in the boundary condition where the archwire is fixed directly to the crowns. This boundary condition makes the finite element simulation easier and more efficient when investigating the effects of force angulation on the movement pattern of the whole dentition.

CONCLUSION

By using a 3-dimensional finite element simulation, the mechanics of total distalization of the mandibular dentition were clarified. The following conclusions were reached:

1. The movement pattern of the whole dentition can be controlled by angulation of the distalization force. Elastic deflection of the archwire increases tipping of the anterior teeth. A clearance gap between the archwire and the bracket slot may cause tipping, depending on their initial relative positions.
2. Selective use of force angulation by means of TSADs with a biomechanical understanding can result in proper distalization of the whole mandibular dentition.

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