Original Article

Effects of different distalization directions and methods on maxillary total distalization with clear aligners: a finite element study

Kyoung-Ho Kwak[a]; Sewoong Oh[b]; Youn-Kyung Choi[c]; Sung-Hun Kim[d]; Seong-Sik Kim[d]; Soo-Byung Park[d]; Yong-Il Kim[e]

ABSTRACT

Objectives: To analyze the effects of maxillary tooth distalization by clear aligner (CA) treatment with variations in the angular direction of the distalization force, presence of attachments, and force-application method used.

Materials and Methods: A finite element model containing alveolar bone, dentition, and periodontal ligament was constructed. Analytical model groups were as follows: (1) distalization with buttons (without attachments), (2) buttons on canines (with attachments), (3) precision cuts on the canines (without attachments), and (4) precision cuts on the canines (with attachments). A distalization force of 1.5 N was applied to the button or precision cut at $-30°$, $-20°$, $-10°$, $0°$, $10°$, $20°$, and $30°$ to the occlusal plane.

Results: As the direction of force approached $+30°$, the dentition inclined posteriorly. The posterior movement pattern was significantly influenced by the presence of an attachment and the direction of force, rather than the area where the force was applied. Distal inclination was dramatically reduced with attachments. A disengagement or deformation of the CA may reduce the distalization efficiency of the dentition or move the dentition in an inappropriate direction.

Conclusions: Attachments for efficient distalization by the CA are necessary. The use of miniscrews in the direction of force parallel to the occlusal plane is more advantageous than the use of Class II elastics. Due to CA deformation, distalization with the button on the canines can be more effective for distal movement of the maxillary dentition. (*Angle Orthod.* 2023;93:348–356.)

KEY WORDS: FEM; Clear aligner; Total retraction; Force direction; Attachment; Precision cut

The first two authors contributed equally to this work.

[a] Adjunct Assistant Professor, Department of Orthodontics, Pusan National University, and private practice, Busan, South Korea.

[b] Resident, Dental Research Institute, Pusan National University Dental Hospital, Yangsan, South Korea.

[c] Clinical Associate Professor, Department of Orthodontics, Pusan National University Hospital, Busan, South Korea.

[d] Professor, Department of Orthodontics, School of Dentistry, Pusan National University; Dental Research Institute, Yangsan, South Korea.

[e] Professor, Department of Orthodontics; and Dental Life and Science Institute, Pusan National University, and Dental Research Institute, Yangsan, South Korea.

Corresponding author: Dr Yong-Il Kim, Dental and Life Science Institute, School of Dentistry, Pusan National University, Geumoro20, Mulgeumeup, Yangsan 50612, Republic of Korea (e-mail: kimyongil@pusan.ac.kr)

Accepted: December 2022. Submitted: July 2022.
Published Online: January 31, 2023

INTRODUCTION

As clear aligner technology has made dramatic progress in recent years, its use has become more practical even in mild-to-severe malocclusion cases.[1,2] According to Hennessy and Al-Awadhi,[3] clear aligner treatment (CAT) can achieve expansion, constriction, intrusion, extrusion, tipping, buccolingual tipping, and rotation of the anterior dentition through tooth movement.[3] Unfortunately, the overall accuracy of CAT's tooth movement is reported to be only 41%. However, it has shown an accuracy of 87% for molar distalization.[4,5]

The key to nonextraction treatment of Class II malocclusion is maxillary molar distalization. As previously reported, CAT is able to provide molar distalization with high accuracy through sequential movement.[6] In a study by Ravera et al.,[7] CAT was found to produce 2.25 mm of maxillary first molar distalization using Class II elastics and attachments without mesiodistal tipping of the molar.

 DOI: 10.2319/072622-519.1

Table 1. Properties of Materials Used in This Study

Material	Young's Modulus, MPa	Poisson's Ratio
Alveolar bone	13,700	0.3
Teeth	19,600	0.3
Plastic aligner	528	0.36
Composite attachment	12,500	0.36
Button (stainless steel)	200,000	0.3
Periodontal ligament	0.69	0.45

In conventional bracket-wire orthodontics, temporary anchorage devices (TADs), such as buccal miniscrews and miniplates, are used for total distalization. Oh et al.[8] reported that 1.4–2.0 mm total retraction of the maxillary dentition was observed when using a buccal miniscrew. Furthermore, Yamada et al.[9] reported that 2.8 mm of total retraction of the maxillary dentition was observed with a buccal miniscrew.[9] Therefore, if the skeletal anchorage system is adapted to CAT, it would be possible to increase the efficiency of tooth movement and expand its range of utilization in treatment.

The finite element method (FEM) is a reliable research method that can predict orthodontic tooth movement in the field of orthodontics and dentofacial deformity. The tooth movement pattern according to force angulation was analyzed and visualized using FEM by Kwamura et al.[10] Although the pattern of tooth movement of CAT has been actively studied, biomechanical studies using a miniscrew and CAT in distalization treatment are still lacking.

The aim of this study was to analyze the displacement trends of maxillary tooth distalization following CAT using FEM with variations in angular directions of the distalization force, presence of attachments, and force application methods (button vs precision cut).

MATERIALS AND METHODS

A 3-dimensional (3D) model containing the alveolar bone, dentition, and periodontal ligament (PDL) was built. A 3D model of the dentition and maxilla were obtained using 3D Slicer by segmentation and extraction from cone-beam computed tomography data (PaxZenith 3D, Vatech Co, Seoul, Korea).[11] Tooth positions were minimally readjusted according to Andrew's six keys to normal occlusion. The PDL and aligner were created on the outer edge of the tooth with a 0.25-mm offset and an aligner with a 0.5-mm offset using MATLAB (version 2020b, MathWorks Inc, Natick, Mass). Only the right side was modeled, assuming left-right symmetry.

All components were considered homogenous linear elastic materials (Table 1 and Figure 1).[12–14] The property of the composite attachment was based on data from the manufacturer (3M, St. Paul, Minn). FEM

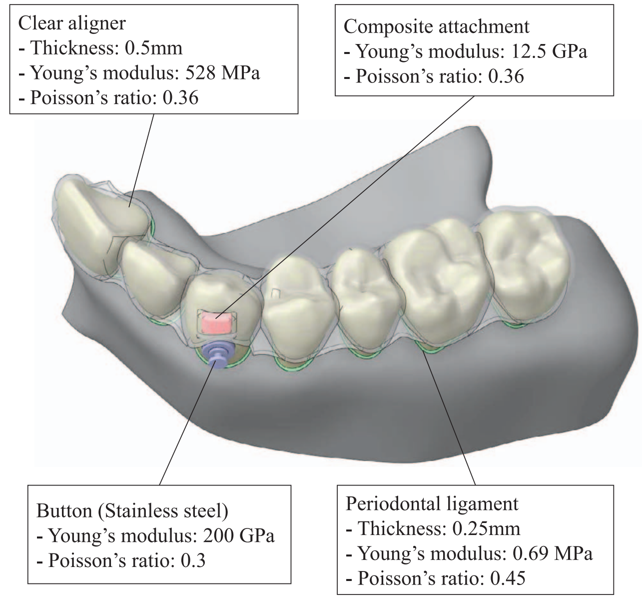

Figure 1. Finite element model for maxillary distalization with a clear aligner.

software, ANSYS 2021R (ANSYS Inc, Canonsburg, Penn) was used. The interfacial condition was set as frictional contact ($\mu = 0.2$) between the tooth and the aligner, and the remaining structures were assumed to be bonded contacts. After completing the mesh convergence study based on errors in canine displacement (below 0.1% of change), the mesh size was determined as follows:

- Type of element order: linear
- Average nodes: 1617260
- Average element: 8763064

Four FEM models were built to clarify the difference between the displacement pattern when posterior retraction was applied directly to the canine (button on canine) or to the aligner (precision cut on canine), with or without attachments. The analytical models are listed in the following order (Figure 2): (1) group A1: distalization with a button on the canine (without attachment), (2) group A2: with a button on the canine (with attachment), (3) group B1: with a precision cut on the canine (without attachment); (4) group B2: with a precision cut on the canine (with attachment). A horizontal rectangular attachment was designed for the canines (height, 3 mm; width, 2 mm; thickness, 1 mm).

A distalization force of 1.5 N was applied to the canine button for groups A1 and A2 and to the precision cut on the canine for groups B1 and B2 at –30°, –20°, –10°, 0°, 10°, 20°, and 30° to the occlusal plane. Negative values of force angulation indicated that the line of action of the force was in a posterior-

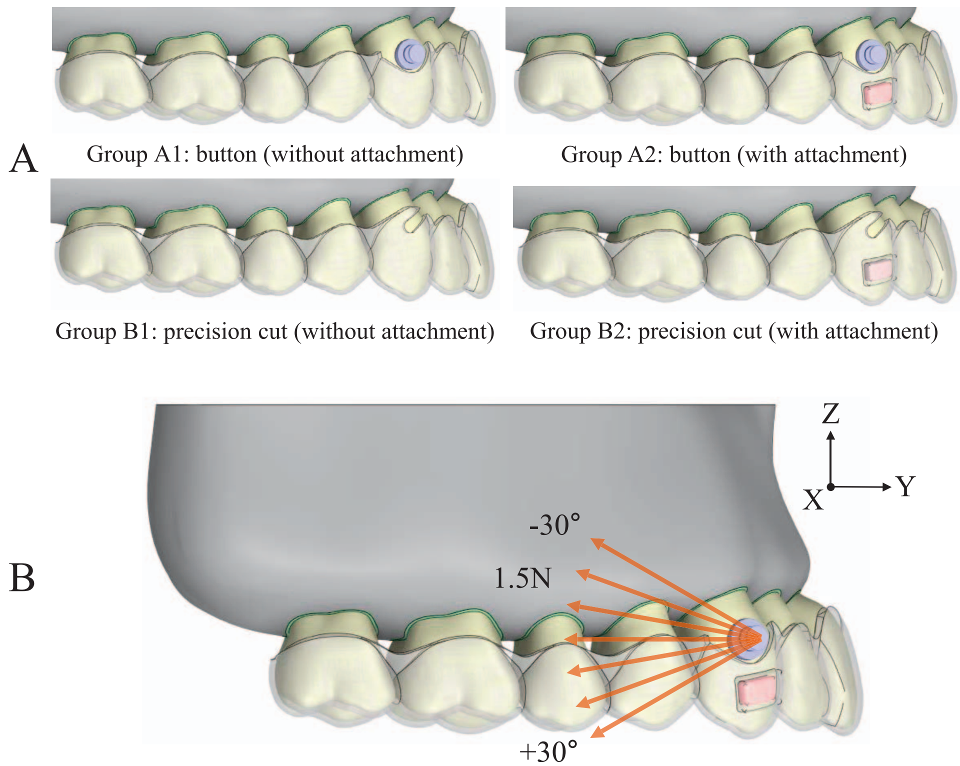

Figure 2. (A) Group A1, distalization with a button (without attachment); group A2, with a button (with attachment); group B1, with a precision cut (without attachment); group B2, with a precision cut (with attachment). (B) Reference coordinate system used for size, orientation, and analysis of results for applied force.

apical direction along the occlusal surface, while positive values indicate the opposite. The mesial incisal point of the central incisor and cusps of the first molars on both sides were used to define the occlusal plane.

Each tooth movement was divided into translational and rotational components based on the estimated center of resistance (one-third of root height for anterior dentition, furcation area for posterior dentition) and tooth axis using MATLAB. The $+x$, $+y$, and $+z$ axes in the translation indicated movement from the occlusal plane to the right (lateral), anterior, and apical planes, respectively. The positive value of rotational motion represented buccomesial rotation, mesial-tipping, and mesial-in rotation based on the long axis of the tooth (Figure 2B).

RESULTS

Analysis of Tooth Movement Patterns in Each Experimental Group Based on the Direction of Force Applied

In all four groups, the central incisors, canines, and molars showed increased linguoversion from $-30°$ to $30°$ (Figures 3A, 4A, and 5A). However, the canines were buccally tipped when the force application angles were $-30°$ and $-20°$ in group A1 and $-30°$ in group B1 (Figure 4A). Groups A2 and B2 showed the most significant distal movement of canines at $-10°$ force angle; no significant difference according to the angle changes was observed (Figure 4C). The amount of distal movement of first molars increased as the angle of force applied increased. Distal tipping was observed as the force angle increased (Figure 5B).

Comparison of Movement Patterns for Each Tooth With and Without Attachments

Lingual tipping was significant for the central incisors when there was no attachment (groups A1 and B1). Buccolingual tipping of the canines was more affected by force angle when there was no attachment. Although groups A1 and B1 showed sizeable distal movement, they also showed a strong tendency toward distal tipping. Distinctively, the canine tended to have mesial-out rotation in group A1. In the canine, when force was applied either through the clear aligner (CA; groups B1 and B2) or directly but offset by the attachment, the tendency of canine rotation was decreased. However, when force was applied only to the canine, severe rotation was observed. More distal tipping appeared when there was no attachment to the first molar than when attachment was present.

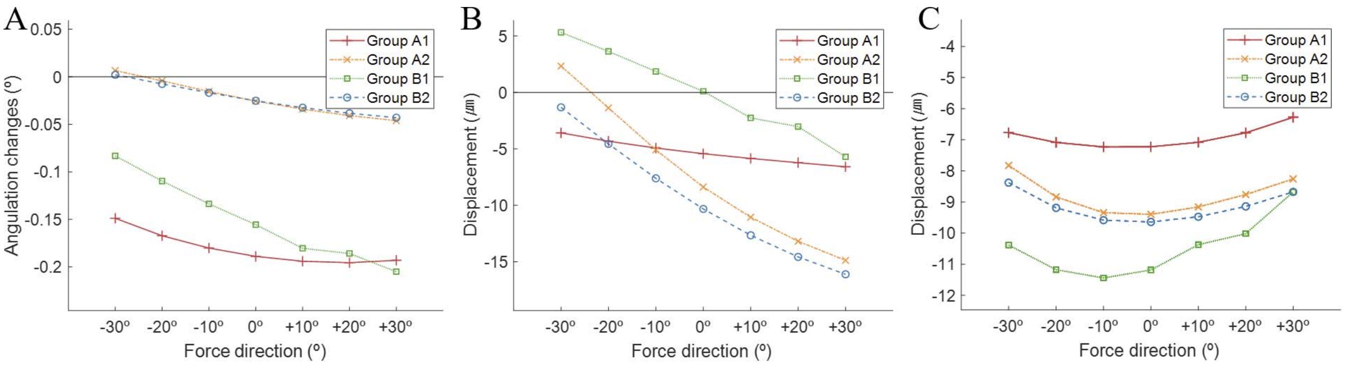

Figure 3. Translation and rotational displacements of the maxillary central incisors for each group and the direction of the retraction forces. (A) Buccolingual angulation (degree). (B) Apicocoronal displacement (μm). (C) Anteroposterior displacement (μm).

Comparison of Movement Patterns for Each Tooth Related to Precision Cut and Lingual Button

Among groups A2 and B2, which had attachments, the central incisors extruded further, and the canines showed more linguoversion, posterior movement, and distal tipping in group B2.

Among groups A1 and B1, which had no attachment, the central incisors showed more posterior movement and the canines had more linguoversion in group B1, while the canines in group A1 showed considerable mesial-out rotation. In group B1, the first molars showed linguoversion and were more prone to mesial-out rotation; less rotation occurred in group A1.

DISCUSSION

Maxillary molar distalization is a critical step in the treatment of Class II malocclusion. Sequential distalization of the maxillary molar is often used for CAT with proper attachment of Class II elastics.[6,7] Unfortunately, when Class II elastics are used, side effects such as mesialization, extrusion of the mandibular molar, lingual tipping, and extrusion of maxillary incisors can occur.[15] However, in the conventional bracket-wire system, various types of distalization patterns can be made depending on the location and retraction direction of TADs.[16] The significant difference between a distalization pattern achieved by using Class II

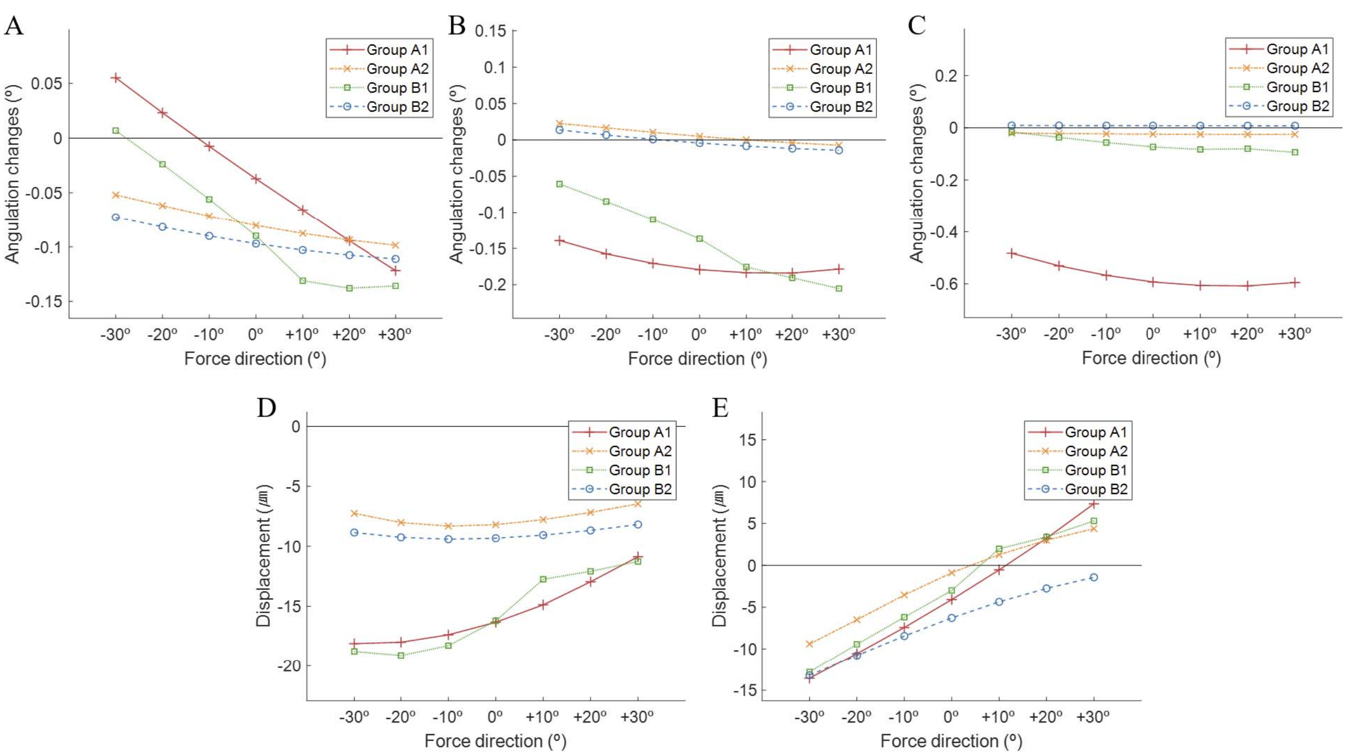

Figure 4. Translation and rotational displacements of the maxillary canine for each group and the direction of the retraction forces. (A) Buccolingual angulation. (B) Mesiodistal angulation. (C) Rotation. (D) Anteroposterior displacement (μm). (E) Apicocoronal displacement (μm).

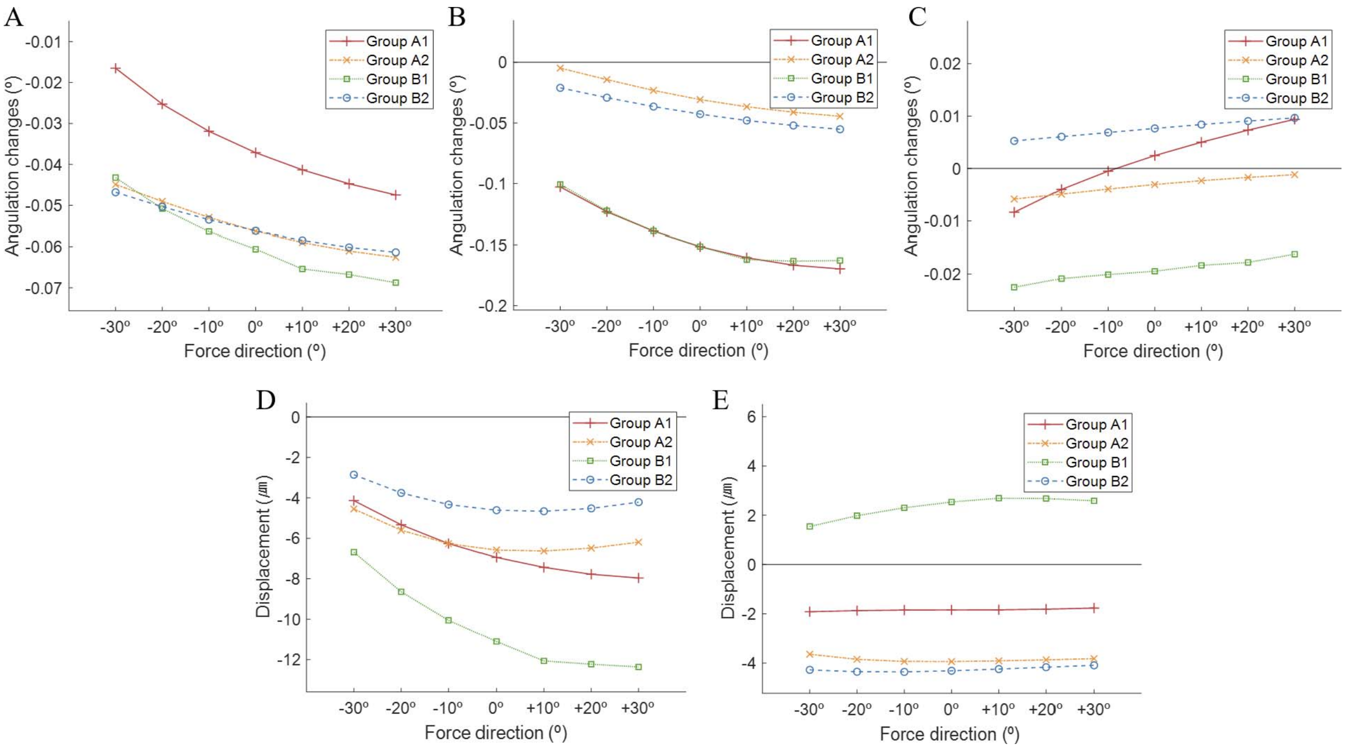

Figure 5. Translation and rotational displacements of the maxillary first molar for each group and the direction of retraction forces. (A) Buccolingual angulation. (B) Mesiodistal angulation. (C) Rotation. (D) Anteroposterior displacement (μm). (E) Apicocoronal displacement (μm).

elastics and using TADs is the direction of retractive forces applied to the maxillary dentition and their side effects. In this study, the difference in distalization patterns related to the direction of forces and the different methods used (buttons on canines and precision cuts) was evaluated.

When comparing tooth movement related to the direction of the force, all groups showed movement patterns similar to those of the conventional bracket-wire system. As the direction of the force approached +30°, the entire dentition became inclined posteriorly. As a result, extrusion and linguoversion of the incisors, extrusion and posterior inclination of the canines, and posterior inclination of the first molars occurred (Figure 6A–D). Clinically, clockwise rotation of the occlusal plane occurred more dramatically when using Class II elastics than when using miniscrews.

This result was consistent with previous FEM studies using brackets and wires,[10] although several differences were shown. The main differences were the intrusion of the incisors in groups A2 and B1 when force was applied in the direction of −30° (Figure 6F,G). Other differences included the intrusion of the canine and the rotation pattern of molars according to the force direction in group B2 when force was applied in the direction of +30° (Figure 6D). Hence, these results demonstrated differences from the conventional bracket-wire system for several reasons. The first reason was the "disengagement" phenomenon between the dentition and CA, and second was the deformation of CA.

The disengagement phenomenon was conspicuously observed when a force was applied directly to the CA. In group B1, when a force was applied upward to the occlusal plane, the CA deviated from the occlusal plane and caused distal tipping rather than translational movement of the dentition. Therefore, the direction of force gradually changed downward in the occlusal plane, and the amount of posterior movement of the canine rapidly decreased (Figures 4–6). Simultaneously, lingual inclination of the incisors and posterior inclination of the canines and molars were prominent in group B1. However, when the retraction force was applied over +10°, engagement was lost. In addition, the lingual tipping of the incisors and distal tipping of the canines and molars were clearly reduced.

This disengagement phenomenon was also observed when a force was applied directly to the canine. In group A1, extrusion, linguoversion, and rotation of the canine were caused by the posterior retraction force applied to the canine. In addition, CA disengagement occurred, and the canine moved posteriorly. Compared with the other groups, linguoversion of the incisors and distal tipping of the canines and molars were more dramatic.

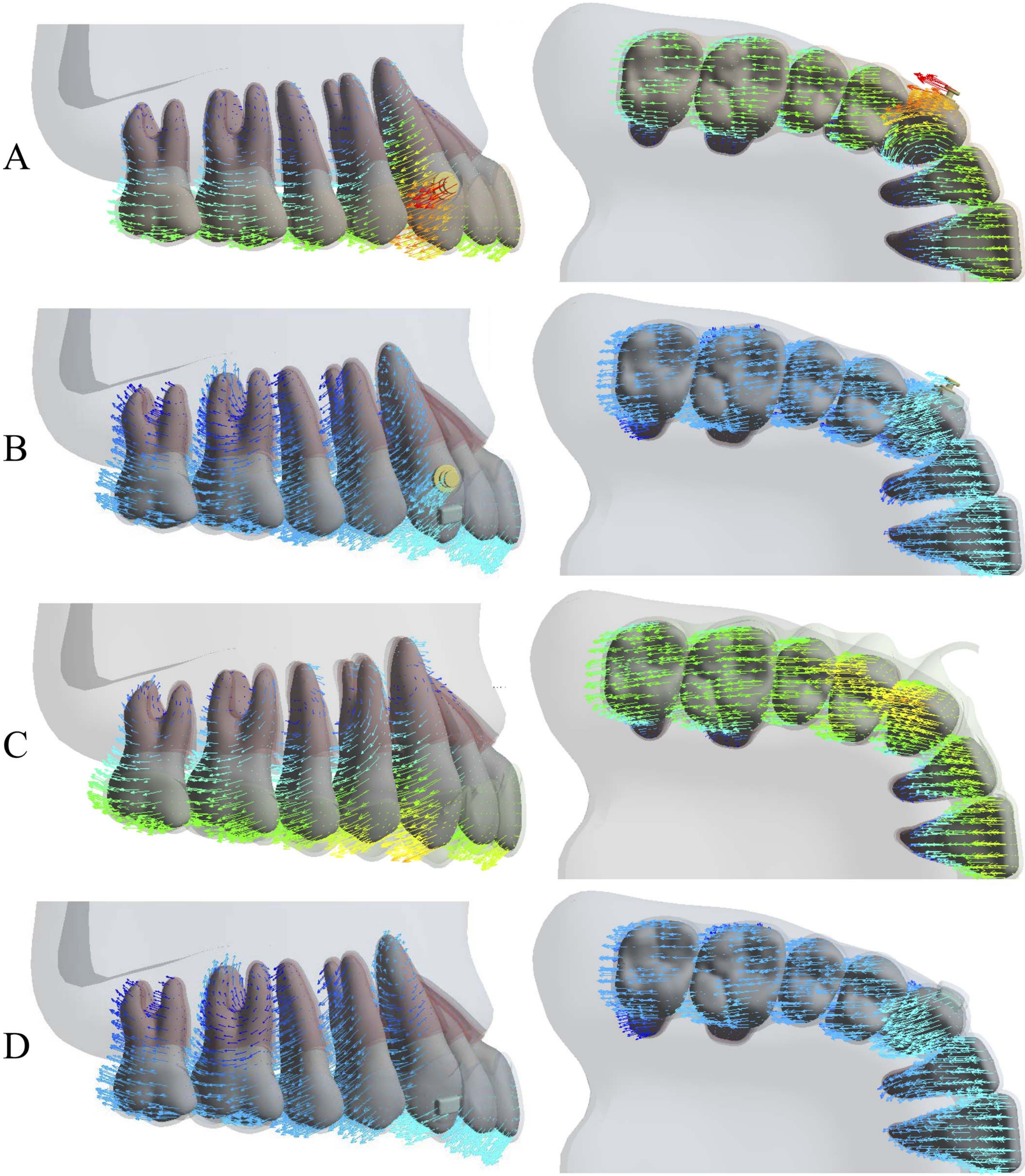

Figure 6. Distalization patterns according to the direction of applied forces. (A) Group A1, +30°; (B) group A2, +30°; (C) group B1, +30°; (D) group B2, +30°; (E) group A1, –30°; (F) group A2, –30°; (G) group B1, –30°; and (H) group B2, –30°.

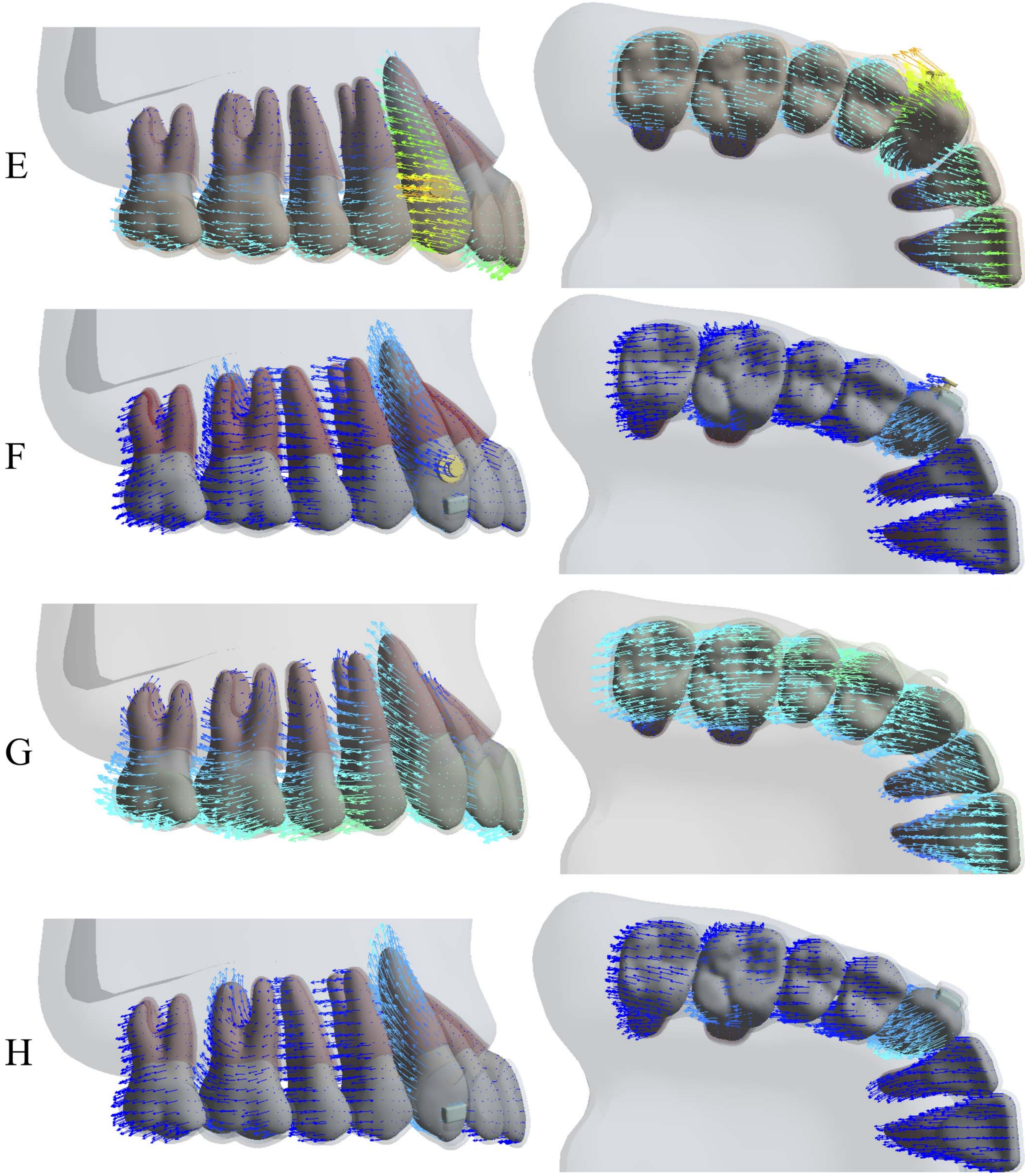

Figure 6. Continued.

The disengagement phenomenon between a specific tooth and CA reduces the distalization efficiency of the dentition or moves the teeth in an inappropriate direction. For this reason, attachment to the part that transmits the force is necessary. According to a distalization study using finite element analysis with attachments from the maxillary canine to molars,[17] if the attachment is attached to teeth other than the canine and if the force is applied in an opposite arch, it is possible to prevent the occurrence of the disengagement phenomenon in other teeth.

The second significant phenomenon was deformation of the CA. Gomez et al.[18] hypothesized that deformation of the CA would cause intrusion of the canine during distalization of the dentition. This hypothesis was consistent with the findings in group B2, in which intrusion of the canine occurred when the force was applied even at 30°. Although all other groups showed rotation of the occlusal plane, in group B1, the posterior dentition was extruded regardless of the direction of the force. This was because, while applying force directly to the CA, deformation of the CA was the largest because of the absence of attachment. The effect of deformation is expected to mainly occur in the direction of intrusion of the canine and the direction of extrusion of the molars; however, more in-depth studies are needed to verify this.

Differences with and without attachments were also observed in this study. Groups A2 and B2 (with attachment) showed the largest movement at 0°, $-10°$, and $+10°$ in incisors, canines, and molars, respectively. Groups A1 and B1 (without attachment) showed the largest movement at $-10°$, $-30°$, and $+30°$ in incisors, canines, and molars, respectively. In groups A2 and B2, where the translation movement of individual teeth occurred, the maximum posterior movement was within 0°, which had more horizontal components of force. The inclination was greatly reduced in the incisors, canines, and molars with attachments. As in previous studies, a vertical rectangular attachment caused buccal root movement when the canines were moved posteriorly, and intrusion and tipping occurred without attachments.[19] In particular, the use of optimized attachments provided a countermovement against uncontrolled tipping, enabling root uprighting.[19,20]

In this experiment, in groups A1 and A2 (button group), force was applied to the canine and transmitted to the CA. In groups B1 and B2 (precision cut group), force was applied to the CA in the canine region. Therefore, it can be stated that the posterior movement pattern was significantly influenced by the presence or absence of attachments and the direction of the force rather than by the area where the force was applied. In other words, an attachment is necessary to prevent side effects during tooth movement, and the most effective direction of force for posterior movement is in a direction parallel to the occlusal plane. As it is difficult to perform CAT clinically, the use of miniscrews is more advantageous than Class II elastics, which causes extrusion of other teeth.

This study showed the initial displacement pattern of CAT-based total distalization. However, there were several limitations to this study. First, the FEM results showed only initial displacement and may not reflect actual tooth movement. Second, the thickness of the PDL and CA were assumed to be uniform and homogenous, and the surrounding environments such as gingiva, perioral musculature, and occlusal forces were neglected for computational efficiency. Further study is needed to estimate the transient tooth movement of CAT-based total distalization.

CONCLUSIONS

- Precision cuts induce CA deformation, while a button on the canine produces appropriate rotation.
- Attachments on canines effectively prevent inappropriate rotation and translation for distalization in CAT with precision cuts and buttons on canines.
- The direction of force parallel to the occlusal plane is efficient for maxillary distalization; however, since it is challenging to apply clinically, the use of a miniscrew with less extrusion of other teeth is recommended.

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