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Original Article

Force direction using miniscrews in sliding mechanics differentially affected maxillary central incisor retraction: Finite element simulation and typodont model

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KEYWORDS
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Abstract *Background/purpose:* En masse retraction was still controversy in orthodontics. The aim of this study was to investigate the effect of force directions created by different miniscrew positions and lever arm heights on maxillary central incisor movement using Finite Element (FE) simulation and a Typodont model.
Materials and methods: A typodont model and 3-dimensional FE were used to simulate en masse anterior teeth retraction in sliding mechanics. The lever arm and the miniscrew positions were varied to change the force direction. The maxillary central incisor displacement was recorded and analyzed.
Results: The typodont results revealed that miniscrew vertical position and lever arm height affected the type of tooth movement. The best control in the vertical plane was achieved by a 7 mm lever arm height and miniscrew 9 mm from the archwire. When the lever arm height and miniscrew were 7 mm from the archwire, the tooth extruded. When the lever arm height was 9 mm and the miniscrew was 7 or 9 mm from the archwire, the tooth intruded. The FE stimulation determined that near bodily movement of the maxillary central incisor was achieved when the lever arm height and miniscrew was 9 mm from the archwire. The highest strain distribution in the periodontal ligament was observed at the apical third of the lateral incisor.
Conclusion: In en masse retraction, the appropriate direction of force or the height of the miniscrew and the lever arm may enable orthodontists to maintain better control of the anterior teeth in sliding mechanics.

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Introduction

In extraction cases, loop and sliding mechanics are commonly used for space closure during orthodontic treatment.[1–4] In sliding mechanics, anterior tooth retraction (en masse retraction) can be controlled by using lever arms attached to an archwire. En masse retraction was defined by Daskalogiannakis as retracting multiple teeth together as a group, usually the four incisors or all anterior teeth.[5]

Advances in miniscrew use have made universal tooth movement in orthodontic treatment more feasible and successful in moving the teeth in a desired pattern.[6] The direction of the retraction force is controlled by the force vector, which is influenced by the lever arm height and position on the archwire and the miniscrew position. Efficient orthodontic tooth movement requires understanding the relationship between the line of action of the force and the center of resistance (CR) of a tooth. A single force passing through the CR results in bodily tooth movement.[7,8] When the lever arm was placed mesial to the canine, at the bracket slot level, uncontrolled lingual crown tipping of the incisor occurred and the anterior archwire segment was deformed downward. At a lever arm height of 5.5 mm, bodily movement was found and the archwire was deformed less. When the lever arm height exceeded 5.5 mm, there was lingual root tipping and the anterior archwire was raised upward.[7] In addition, the direction of force at an 8 mm miniscrew position nearly achieved bodily tooth movement compared with a 4 mm miniscrew position. Thus, the vertical component of the force produces intrusion or extrusion of the entire dentition.[9]

The location of the CR is important in controlling tooth movement and the CR may change due to root length and alveolar bone height.[10] The CR of a single tooth and a group of teeth is not the same. Burstone found that the CR of an upper central incisor was located 30–40% of the distance from the alveolar crest to root apex.[11] Many studies tried to determine the location of the CR,[8,12–14] with Jung and Kim stating that the CR of the maxillary six anterior teeth is located between the lateral incisor and canine roots and 6.76 mm above the cervical area.[15]

For en masse anterior retraction, the working rectangular wires with a miniscrew and lever arm for sliding mechanics can be 0.019 × 0.025-inch stainless steel (SS) for a 0.022 × 028-inch SS bracket slot or 0.016 × 0.022-inch SS for a 0.018 × 025-inch SS bracket slot.[16]

The essential tools to study orthodontic tooth biomechanics ex vivo are finite element (FE) simulation and Typodont models.[17,18] Although some studies have analyzed tooth displacement in sliding mechanics during en masse retraction using FE simulation and typodont models, the tooth movement analyses using non-parallel force directions are not conclusive.[7,8,19–22] Moreover, root resorption can occur during orthodontic treatment.[23,24] The aim of the present study was to investigate the effect of different force directions created by different orthodontic miniscrew positions and lever arm heights on maxillary central incisor movement using FE simulation and a Typodont model.

Materials and methods

Typodont model

To exclude the confounding factors present in a clinical study, a typodont (Dentaurum GmbH & Co. KG, Ispringen, Germany) with standardized maxillary plastic teeth, except for the first premolars and third molars, with a metal sheet cover at the root area (Fig. 1A) was used. The typodont teeth were bonded with 0.018 × 0.025-inch metal brackets (Gemini; 3M Unitek, Monrovia, CA, USA) using Transbond XT (3M Unitek) and light cured for 40 s and sequentially aligned using 0.014-inch NiTi, 016-inch NiTi, 018-inch NiTi, and rectangular 0.016 × 0.022-inch NiTi archwire. The dentition was completely aligned and leveled and a silicone mold was made to record the initial tooth alignment and level (Fig. 1 A, B, C, and D) and this was used to set the teeth to a standardized position after each experiment.[22] To reset the maxillary teeth for subsequent experiments, the upper typodont teeth were seated in the silicone mold and melted modeling wax (Cavex, Haarlem, The Netherlands) was poured in the mold. After the wax cooled, the wax/tooth model was removed from the silicone mold and assembled whole on the typodont. The distance from the base of the wax to the interproximal gingival crest of the central incisor was 36.5 mm, and the space between the canine and 2nd premolar was 6.5 mm and the intercanine width was 35 mm. The posterior portion of the typodont was replaced by cold-cure acrylic resin to stabilize the anchorage teeth. A 0.016 × 0.022-inch SS archwire (ORMCO, CA, USA) was engaged in the 0.018 × 0.025-inch metal brackets. The lever arm and simulated miniscrews were bilaterally placed 7 and 7, 7 and 9, 9 and 7, or 9 and 9 mm, respectively, between the maxillary lateral incisor and canine and between the second premolar and the first molar, respectively. The spaces were closed using Superelastic 6 mm nickel-titanium closed-coil springs that were attached on the lever arm and simulated miniscrew. A 2 N (200 g) force was applied between the simulated miniscrews and lever arms.[19] The typodont was immersed in a digital water bath at 45 °C for 120 min (min). Digital photographs were taken every 20 min. A ruler was fixed on the table as a measurement reference and the horizontal

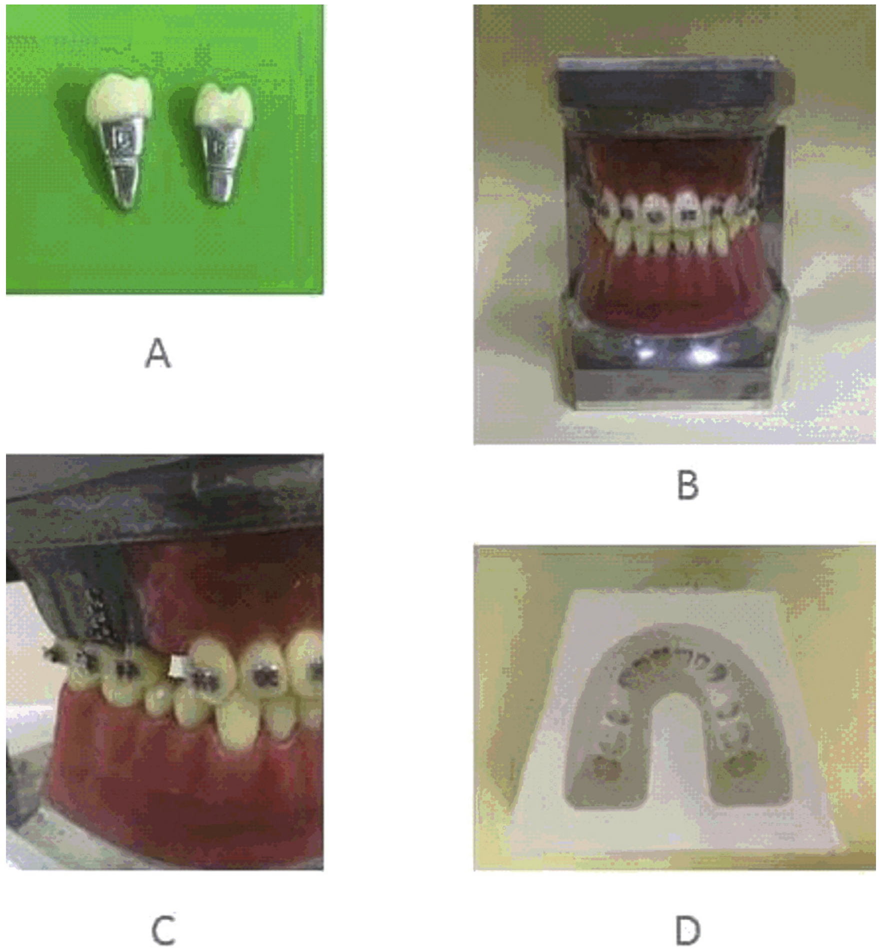

Figure 1 (A) Typodont tooth, (B) Typodont model, (C) Simulated miniscrew, and (D) Silicone mold.

and vertical movement of the incisal edge of the upper central incisors was measured using the ImageJ-NIH processing programs.[22] The 0 min measurement was subtracted from the 120 min measurement to evaluate vertical movement of the maxillary central incisor. When a negative value was found, the incisal edge had intruded, when a positive value was found, the incisal edge had extruded. Each en masse retraction miniscrew and lever arm arrangement experiment was performed 3 times.

Simulation study

Three-dimensional (3D) geometric model construction

The geometric model was constructed based on a dental study model (i21D-400C; Nissin Dental Products, Kyoto, Japan).[7,17,18] Images of the model were taken using dental cone-beam computed tomography (i-CAT, USA). The 0.018-inch bracket slots (Gemini; 3M Unitek) were constructed with a 0.016 × 0.022-inch SS archwire (ORMCO) engaged into the brackets.

Materials properties

The teeth, periodontal ligament (PDL), alveolar bone, bracket, archwire, and lever arm were separately constructed and considered parametric and homogenous. The archwire and brackets were specified as stainless steel. The PDL and the lamina dura around the roots of the teeth were constructed with an average thickness of 0.25 mm and 0.5 mm, respectively. The material properties of the teeth, PDL, cortical bone, trabecular bone, and stainless steel are shown in Table 1.[22]

Finite element model construction and experimental conditions

The 3D geometric models were converted to FE models with node-to-node connections between the tooth, PDL, and alveolar bone using MSC Patran (MSC; Marc 2015 Software

Table 1 The material properties of the teeth, PDL, cortical bone, trabecular bone, and stainless steel used in the FE simulation.

Material	Poisson's ratio	Young's modulus (Pa)
Teeth	0.3	1.80×10^{10}
PDL	0.3	1.75×10^{9}
Cortical bone	0.3	1.37×10^{10}
Trabecular bone	0.3	1.37×10^{9}
Stainless steel	0.3	2.00×10^{11}

PDL: periodontal ligament.

Corp., USA). An FE mesh of the archwire was created separately from the brackets to allow the archwire to slide freely through the bracket slots. The FE analysis convergence criteria were balanced between action and reaction force. The finite models consisted of 338,354 ten-node tetrahedral elements and 81,459 nodes.

The miniscrews were bilaterally fixed 7 mm or 9 mm above the archwire between the roots of the second premolars and the first molars (Fig. 2). Lever arms 7 or 9 mm in height were bonded to the archwire between the lateral incisors and canines. An orthodontic force of 2 N (200 g) was applied to the lever arms. The 7 and 7, 7 and 9, 9 and 7, or 9 and 9 mm miniscrew position and the lever arm height, respectively, generated 4 different force directions (2 parallel and 2 non-parallel directions) for simulation. The strain distribution in the PDL as a biomechanical response to tooth movement was also determined.

Tooth retraction evaluation

3D FE analysis was performed using a 3D FE program (MSC; Marc 2015 Software Corp., USA). The maxillary central incisor movement patterns were determined by evaluating the difference in the incisal edge level and apex level from their initial location at the end of the retraction. The incisal edge level and apex displacement were calculated and a compared between each force direction. Equal changes (difference in change = 0) indicated that bodily movement has taken place. Difference in the change not equal to zero suggested rotation occurred.

Results

Typodont model results

Maxillary central incisor teeth movement

The horizontal and vertical movement of the maxillary central incisors resulting from the four different force directions due to the 7 and 7, 7 and 9, 9 and 7, or 9 and 9 mm simulated miniscrew position and the lever arm height, respectively, was recorded every 20 min for 2 h (Fig. 3).

The vertical movement of the maxillary central teeth was 0.065 mm in the 7 mm lever arm/7 mm simulated miniscrew group, 0.010 mm in the 7 mm lever arm/9 mm simulated miniscrew group, −0.047 mm in the 9 mm lever arm/7 mm simulated miniscrew group, and −0.129 mm in the 9 mm lever arm/9 mm simulated miniscrew group. The maxillary central incisors were extruded in the 7 mm lever arm/7 mm simulated miniscrew group. The 7 mm lever arm/9 mm simulated miniscrew group demonstrated near bodily movement. In contrast the maxillary central incisors were intruded in the 9 mm lever arm/7 mm simulated miniscrew and 9 mm lever arm/9 mm simulated miniscrew groups (Table 2).

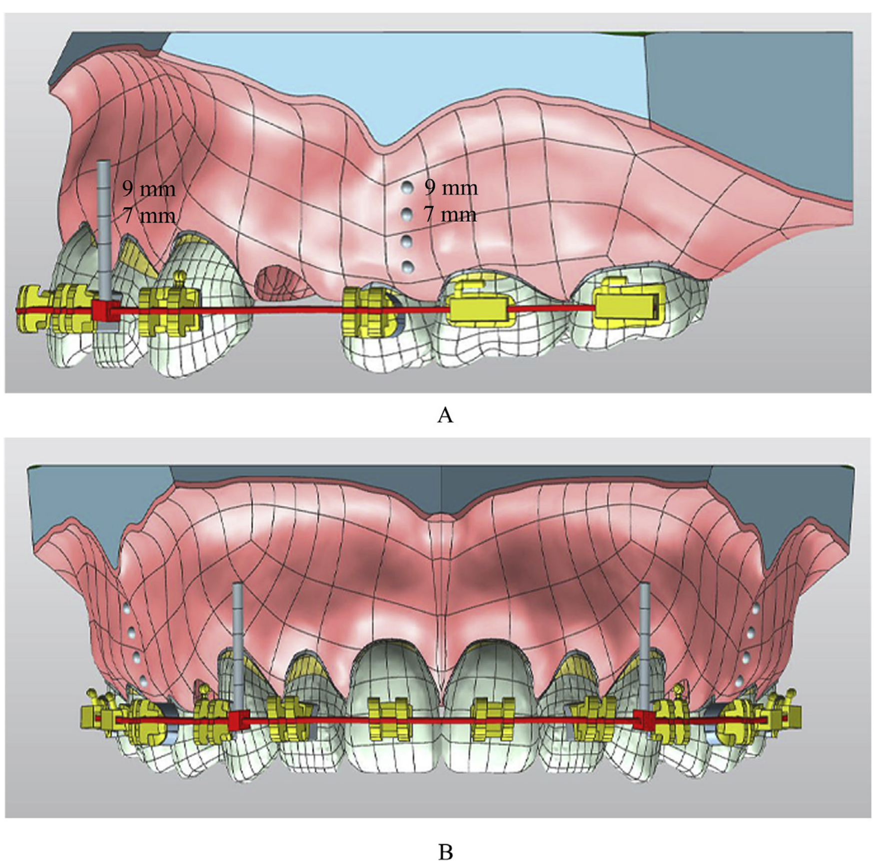

Figure 2 Schematic of the model simulation; (A) Lateral view, (B) Frontal view.

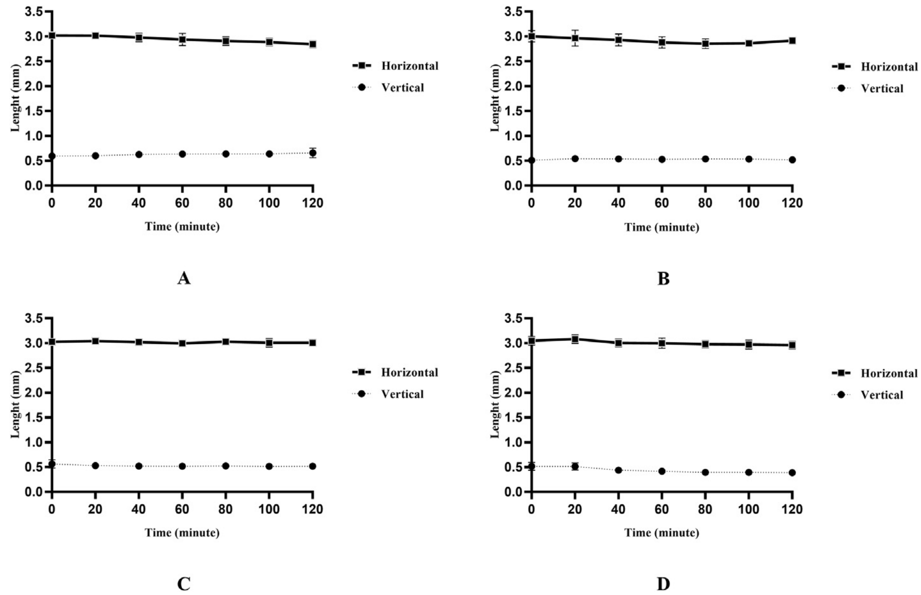

Figure 3 The movement of the maxillary anterior teeth was recorded every 20 min for 2 h. The horizontal movement (Mean ± SD) is shown by the upper line and the vertical movement (Mean ± SD) is shown by the lower line; (A) 7 mm lever arm/7 mm mini-screw, (B) 7 mm lever arm/9 mm mini-screw, (C) 9 mm lever arm/7 mm mini-screw, and (D) 9 mm lever arm/9 mm mini-screw.

Table 2 Vertical movements of maxillary central incisor were recorded for 2 h in different position of lever arm and miniscrew

Lever arm-Miniscrew Level		Vertical movements (Mean ± SD)
Lever arm	Miniscrew	
7	7	0.065 ± 0.103
7	9	0.010 ± 0.058
9	7	−0.047 ± 0.041
9	9	−0.129 ± 0.105

Finite element simulation results

The node displacement of the FE teeth model calculated from their positions before and after applying force demonstrated the incisor edge level and apex displacement of teeth resulting from the FE simulations. The difference in incisor edge level and apex displacement of teeth from their initial location at the end of the retraction for each force direction in the horizontal and vertical plane is shown in Tables 3 and 4, respectively. We found that every force direction evaluated caused maxillary central incisor rotation and the displacement in the vertical plane always corresponded to the horizontal plane (Fig. 4).

Strain distribution in the PDL

The highest strain magnitude was found at the middle third and the largest negative strain was at the apical third of the lateral incisor (Figs. 5 and 6). There were also other highest magnitudes of negative strain at the cervical third of the maxillary central incisor and canine and at the middle third of the maxillary lateral incisor and canine.

Discussion

There were optimum force and other force directions created. The moment vectors are generated depending on the relationship between the direction of the applied force derived from the lever arm height and miniscrew position and the CR of the anterior teeth.[25] When predicting tooth movement, it is important to understand the relationship between the line of action of the retraction force and the CR of the tooth. The height of the retraction force based on

Table 3 The incisal and apical displacement in the sagittal plane in each force direction.

Force direction level		Incisal edge change (mm)	Apical change (mm)	The incisal edge and apical change (mm) (Mean ± SD)
Lever arm (mm)	Mini-screw (mm)			
7	7	5.634E-04	−1.488E-04	7.122E-04 ± 3.881E-05
7	9	5.376E-04	−1.448E-04	6.824E-04 ± 2.855E-05
9	7	4.792E-04	−1.238E-04	6.030E-04 ± 3.821E-05
9	9	3.568E-04	−2.845E-05	3.852E-04 ± 4.507E-05

Table 4 The incisal and apical displacement in the vertical plane in each force direction.

Force direction level		Incisal edge change (mm)	Apical change (mm)	The incisal edge and apical change (mm) (Mean ± SD)
Lever arm (mm)	Mini-screw (mm)			
7	7	2.793E-04	−1.443E-04	4.236E-04 ± 5.681E-05
7	9	2.622E-04	−1.438E-04	4.060E-04 ± 5.890E-05
9	7	2.285E-04	−1.266E-04	3.551E-04 ± 6.336E-05
9	9	1.253E-04	−8.686E-05	2.121E-04 ± 8.663E-05

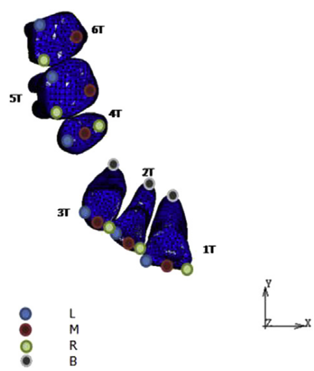

Figure 4 Measuring points of the teeth (L, M, R and B). L - distal central incisor edge, M - middle central incisor edge, R - mesial central incisor edge, and B - central incisor root apex. In this study, M and B were used to calculate tooth movement.

lever arm length affects the type of anterior tooth movement (lingual crown tipping, lingual root tipping, or bodily movement).[7,19,26,27] Bodily movement can be achieved by a power arm whose height is approximately at the same level as the CR.[27] Tominaga et al. found by FE that bodily movement happened when the lever arm height was 5.5 mm.[7] However, our typodont results indicated that the 7 mm lever arm and 9 mm high simulated miniscrew shifted the line of force to the incisor CR and above the posterior teeth CR. In contrast, the 7 mm lever arm height and simulated miniscrew position line of action was below the CR, causing the anterior and posterior segment to rotate around the CR, and central incisor extrusion. In addition, the 9 mm lever arm height and 7 or 9 mm simulated miniscrew position made the direction of the force beyond the CR, causing central incisor intrusion.

There are other factors affecting tooth movement to consider, play between a bracket and archwire can cause the anterior teeth to tip until the archwire binds in the bracket slot.[20,21] Furthermore, friction at the bracket-archwire interface affects tooth movement.[28,29] Tooth movement occurs when the applied forces overcome the friction at the bracket slot-archwire interface.[30,31] Static friction is the least force needed for movement to begin, while kinetic friction or moving friction is the force required for the motion of a solid object over another at a constant speed.[32,33] Wire sizes, alloys and narrow single brackets were associated with lower amounts of friction compared with wider brackets.[30,31] Moreover, Tominaga, et al.[20]found that torque acting on the anterior tooth became applicable with smaller archwire/bracket clearances and this indicated that play in the vertical dimension had a greater impact on the movements of the anterior teeth than in the horizontal dimension. It was considered that the greater the play between the archwire and the bracket, the lesser lingual root tipping moment.

In en masse retraction, the miniscrews are usually placed in the buccal side of the maxillary alveolus between the roots of the maxillary second premolar and first molar.[9,19,34,35] Thus, there is an anatomical constraint where the miniscrew can only be placed on the attached gingiva. The present study demonstrated that the optimal position that generated nearest bodily movement of the maxillary central incisor occurred

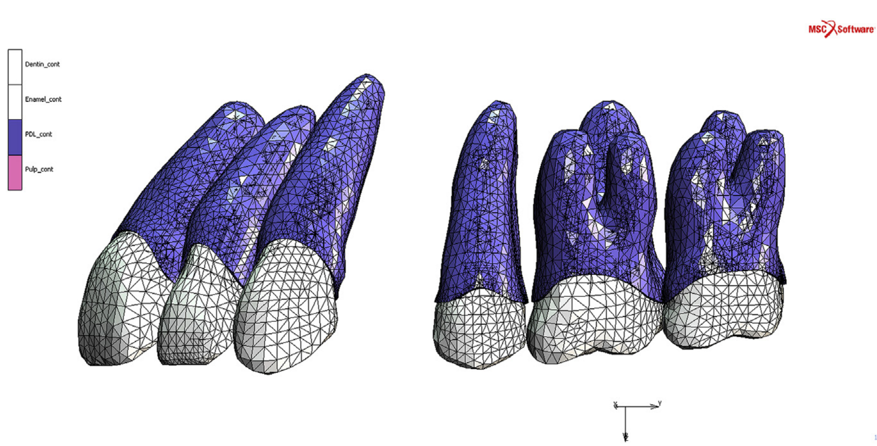

Figure 5 Periodontal ligaments (purple) in the model.

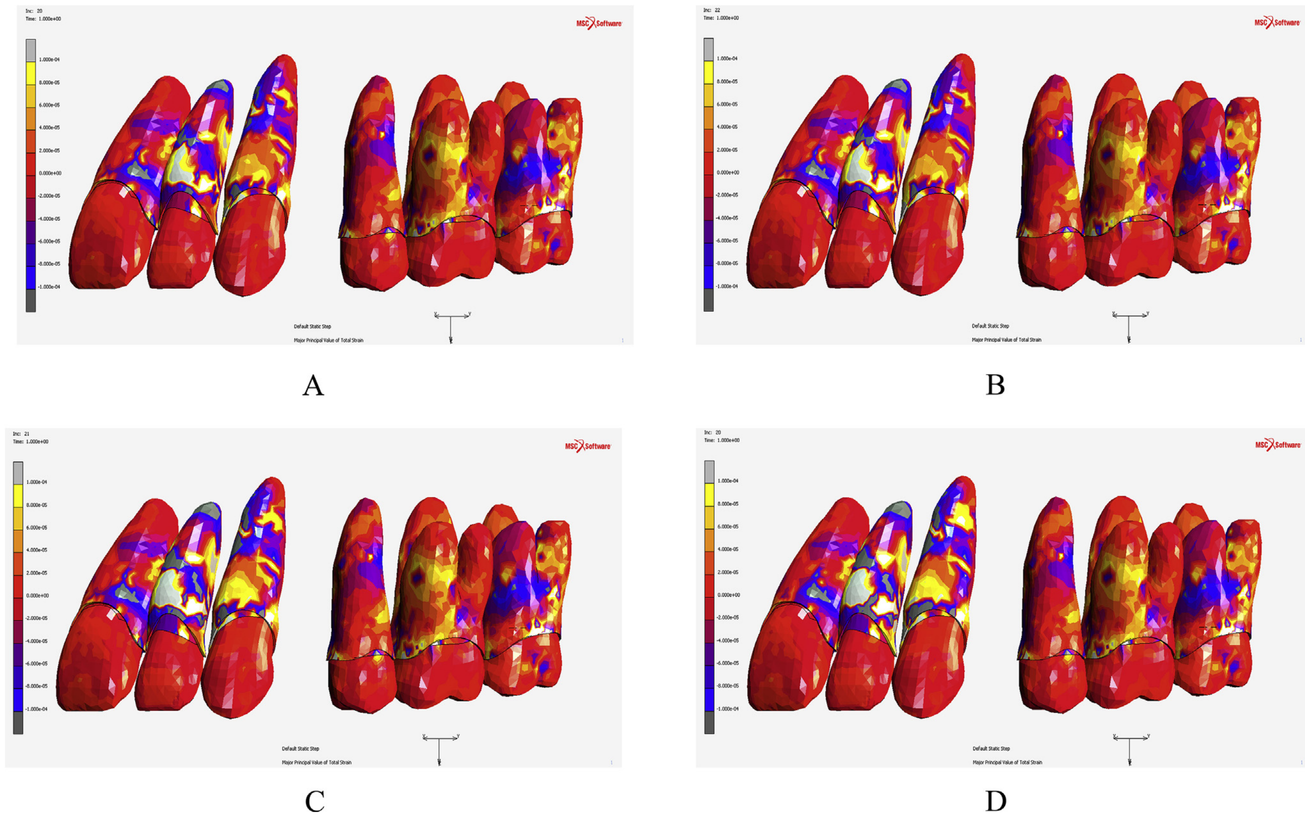

Figure 6 Tooth strain distribution patterns after maxillary anterior teeth retraction; (A) 7 mm lever arm/7 mm mini-screw, (B) 7 mm lever arm/9 mm mini-screw, (C) 9 mm lever arm/7 mm mini-screw, and (D) 9 mm lever arm/9 mm mini-screw.

when the lever arm height and miniscrew were 9 mm above the brackets. (The difference in incisal edge and apical change (mm) were arranged from maximum to minimum value in both.)

In this study, to create the optimum force direction for maxillary central incisor bodily movement, there were different lever arm heights in the Typodont model and FE simulation. However, the same miniscrew position was used in both simulations. Thus, clinical studies are necessary to confirm these results.

Additional information regarding the biomechanical changes to evaluate the relationship of tissue remodeling and root resorption in response to en masse retraction can be obtained from observing the strain distribution patterns in the PDL. The distribution patterns of the displaced roots are shown as contour lines with color magnitude to represent PDL deformation with regard to force. The finding that the strain pattern generated was highest at the lateral incisor roots was consistent with the study of another study.[36,37] Reiman S, et al.[36] found that the lateral incisors had significantly strain in the PDL higher than at another anterior teeth due to the inhomogeneous movement of the individual anterior teeth.

It may be supposed that the lateral incisors might higher bone remodeling rate, while bone remodeling is correlated to PDL strains.

Conflicts of interest

There is no potential source of conflict of interest.

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