3D Finite Element Study of En masse Retraction of Maxillary Anterior Teeth in Two Typical Force Directions

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Objective: *To investigate the displacement and stress distribution of maxillary anterior teeth during retraction using the finite element method.*
Methods: *A three-dimensional finite element model of six maxillary anterior teeth with a straight wire appliance on intermaxillary bone was established in ANSYS 8.1. Retractions in two typical force directions were simulated: case 1 simulated routine anterior tooth retraction by a force of 150 g applied between the anterior hook of 2.0 mm and the first molar tube; case 2 simulated anterior tooth retraction by a force of 150 g between the anterior hook of 4.0 mm and the implant 10.0 mm towards the gingiva from the first molar tube.*
Results: *This finite element model was highly realistic for the simulation of orthodontic tooth movement. In case 1, lateral incisors showed controlled lingual crown tipping movement, while central incisors and canines showed lingual crown tipping movement. Stress concentration was found close to the cervix and root apex of each tooth. In case 2, the displacement and stress level was much higher. Central incisors and canines still showed lingual crown tipping movement while lateral incisors showed bodily retraction and intrusion. In the coronal direction, the lateral incisor root tipped mesially, while the canine root tipped buccally. Stress distribution on central incisors and canines was similar to that in case 1, but the maximum principal stress on labial and lingual surfaces of lateral incisors was mostly compressive stress.*
Conclusion: *During routine anterior tooth retraction by sliding mechanics, the crown of anterior teeth tends to tip lingually. Retraction force passing near the centre of resistance of six anterior teeth makes their displacement and stress distribution more uniform, but their translation is still undetectable. Loading on lateral incisors is greater than that on other teeth and stress concentration at its lingual apex should be considered.*
Key words: *anterior tooth retraction, biomechanics, orthodontics, sliding mechanics, three-dimensional finite element*

With the extensive application of straight wire appliances, en masse retraction of six anterior teeth using a sliding mechanism has been widely used in orthodontic space closure. To achieve bodily movement or translation of anterior teeth, orthodontists should apply either a force passing through the centre of resistance (CRe) of the segment or a horizontal force combined with the proper moment, which produces homogeneous stress distribution in the periodontium. Since the CRe of the six anterior teeth is apical to the brackets, lingual crown tipping of anterior teeth is inevitable with a routine sliding mechanism, even though rectangular stainless steel (SS) archwire is used. Therefore, solutions for managing force systems to achieve en mass retraction of the six anterior teeth is still of considerable interest.

Microscrew implants can provide good anchorage for anterior tooth retraction and can be placed in the most desired locations. It has been reported that the retraction of the six anterior teeth can be achieved with a force

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through the CRe of the six anterior teeth, by altering the occlusal-gingival location of implant and the length of the anterior hook[1,2]. To date, there have been several theoretical and experimental studies focusing on determination of the CRe of maxillary incisors or the six anterior teeth, but no unanimous conclusion has been reached[3,4]. Therefore, a biomechanical study in which these clinical procedures are simulated will provide great insight into clinical treatment.

The finite element method (FEM) is a powerful technique in dental biomechanics, as it is superior in the calculation of the stress and strain of various complex structure[5,6]. Previous studies usually focused on a single tooth subjected to force and moment. In the present study, a finite element model of six maxillary anterior teeth was established and the effects of force direction on the tooth displacement pattern was investigated.

Materials and Methods

Alignment of the maxillary dental arch

Nissin B3-305(32S) artificial teeth of standard shape were provided by Nissin, Japan. Oriental preadjusted orthodontic brackets (with a 0.559-mm slot and Kosaka prescription, TOMY, Japan) were bonded to the midpoint of the facial axis of the clinical crown with Transbond light-cure adhesive (3M, MN, USA). An archwire of 0.533×0.635 mm stainless steel (SS), according to the average standard arch form recommended by TOMY, was ligated to the brackets, and the teeth were aligned[7]. All teeth were fixed with wax, which was later shaped as normal intermaxillary bone.

CT scanning

The brackets and archwire were removed and the model was placed with the occlusal plane perpendicular to the horizontal plane. Computerised tomography (CT) images were taken at 0.5 mm intervals. The DICOM data was saved and transformed into the cross-sectional image in bitmap (BMP) file format.

Establishment of three-dimensional (3D) finite element (FE) model

A co-ordinate system was set up as follows: the *x*-axis was in the coronal direction with positive direction from left to right; the *y*-axis was in midsagittal line of the dental arch with positive direction from lingual to labial; the *z*-axis was perpendicular to the occlusal plane with positive direction from occlusal to apical. Each BMP image was viewed in Getdata v2.0, and 20 to 30 key points were selected from the outline of each tooth and intermaxillary bone. These key points were saved as '*k*, *m*, *x*, *y*, *z*' in sequence. The contour of the periodontal ligament (PDL) was obtained using a 0.25-mm offset of the contour of the roots in AutoCAD. All key points edited with ANSYS parameter design language (APDL) were read into ANSYS 8.1 to construct a spline curve, and subsequently the area and entities. The entities of the teeth, PDL and alveolar bone were meshed with the Solid95 element using the auto-meshing function of ANSYS.

An SS archwire of 0.483×0.635 mm was built up with the Beam 4 element in ANSYS according to the equation of the TOMY average standard arch form[7]:

$$y = 2.6195959\text{E} - 5x^4 + 1.3754034\text{E} - 2x^2 - 1.289235$$

Archwire was set at 4.0 mm gingival to the incisal edge of the central incisors. Brackets were built with solid95 elements to connect each tooth to the archwire. The bracket elements shared common nodes with archwire and the crown surface. An SS hook (4 mm long, 0.914×0.914 mm) perpendicular to the occlusal plane was attached to the archwire between the lateral incisor and canine.

Hypothesis condition, boundary condition and load type

Teeth, PDL, alveolar bone and stainless steel in this model were assumed to be isoparametric and homogenous materials. With reference to previous studies, the Young's elastic modulus and Poisson's ratio of materials are listed in Table 1[5,6,8].

To study the en masse retraction of the six anterior teeth, the back and top of the anterior maxillary bone is fixed. Vertical and coronal displacements of posterior teeth were ignored so the archwire elements connecting with the brackets of the second premolar, the first molar and the second molar were fixed in the *x* and *z* directions. These elements were free in the *y* direction to simulate sliding between the archwire and brackets or molar tube.

In Case 1, a horizontal retraction force of 150 g was applied from the top of a 2.0-mm hook to the first molar tube. In Case 2, a retraction force of 150 g was applied between a 4.0-mm hook and an implant 10.0 mm apical to the first molar tube.

Model solution and analysis

After the solution, the stress and strain of each node in the model were calculated. Harbouring much higher elastic modulus, the deformation of tooth itself was far less than its displacement resulting from the deformation of the

Table 1 Material properties used in the model

Materials	Elastic modulus (MPa)	Poisson's ratio
Teeth	2.0×10^4	0.3
Bone	1.4×10^4	0.3
PDL	0.68	0.49
Stainless steel	1.4×10^5	0.3

PDL. Displacements of anterior teeth on the right side were analysed. Series of nodes on the facial axis of each tooth were selected and their displacements were extracted to present the movement pattern of the whole tooth.

The distribution of compressive and tensile stresses was identified using a contour plot of maximum principal stress (S1). The area displaying the maximum positive principal stress was translated as the maximum tensile stress area, and the minimum negative principal stress was translated as the maximum compressive stress area. The change of stress in PDL results in alveolar bone reconstruction. Therefore, the stress on the interface of alveolar bone and PDL was analysed.

Results

Establishment of the 3D FE model of archwire–brackets–teeth–PDL

The cross-sectional images of teeth and anterior maxillary bone were obtained from spiral CT. Getdata v2.0 was used to delineate the coordinate of the key points. With the APDL and auto-meshing function of ANSYS, a 3D FE model of six maxillary anterior teeth with the TOMY preadjusted appliance was established, including 186322 nodes, 130616 Solid95 elements and 98 Beam4 elements (Fig 1). Six anterior teeth were erected right in the maxillary bone with normal labial inclination. The crown/root length of the central incisor, lateral incisor and canine were 10/13 mm, 9.5/13.5 mm and 10.5/13.5 mm respectively, with the crown/root ratio ranging from 1.3 to 1.42.

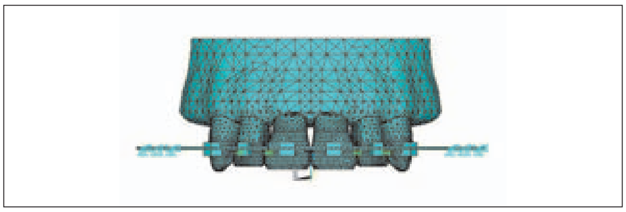

Fig 1 3D finite element model of intermaxillary bone and anterior teeth with the straight wire appliance.

Three-dimensional displacement of each tooth

Figure 2 shows tooth displacement in case 1. In the x-axis, all teeth showed little displacement ($<10^{-6}$ m). In the y-axis, the lateral incisor (U2) showed greater lingual displacement in its crown than in its root, while the crowns and roots of the central incisor (U1) and canine (U3) also showed lingual and labial displacements respectively. In Fig 2, the intersection point of the displacement polyline with the x-axis produced no displacement and could be considered as the instant centre of rotation (ICRo) of the tooth. The ICRo of U2

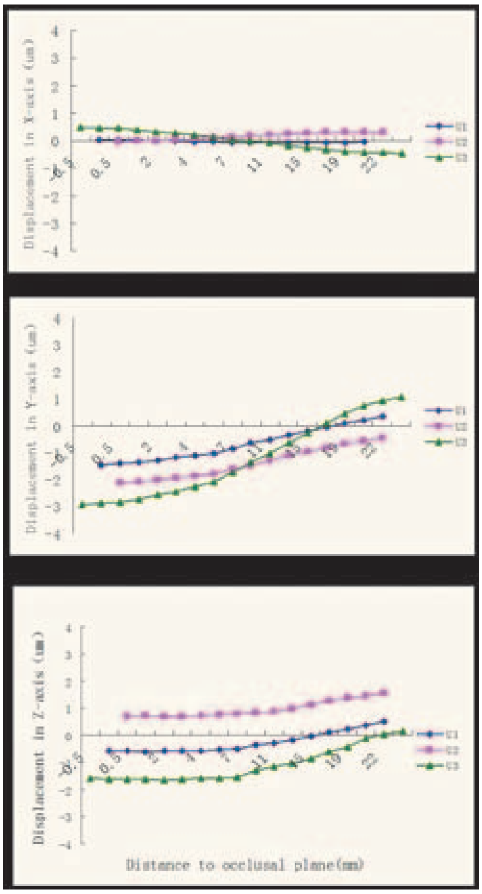

Fig 2 Displacement of each tooth in case 1 (U1, central incisor; U2, lateral incisor; U3, canine).

was about 4.0 mm apical to its apex (controlled lingual crown tipping movement) and the ICRo of U1 and U3 were about 4.0 mm and 7.0 mm coronal to their apices respectively (lingual crown tipping movement). In the *z*-axis, U2 was intruded and U3 was almost extruded, while U1 showed little displacement.

Teeth displacements in case 2 are shown in Fig 3. In the *x*-axis, the root of U2 is tipped mesially whereas the root of U3 is tipped buccally. In the *y*-axis, the crown and root of U2 show almost equal lingual displacement, indicating its bodily lingual movement. The crowns of U1 and U3 were also tipped lingually, and their ICRo was almost the same as in case 1. In the *z*-axis, U1 showed little displacement, but the intrusion of U2 and extrusion of U3 were more significant than those in case 1.

Maximum principal stress (S1) distribution in PDL

Maximum principal stress (S1) in case 1 is shown in Fig 4. S1 on the labial surface of each root ranged from tensile stress at the cervix to compressive stress at the apex. S1 distribution on the lingual surface of U1 and U3 showed an adverse trend, while that of U2 was mostly compressive stress. Stress over 0.045 MPa was considered a stress concentration area, shown in deep blue and red. Maximum tensile stress of 0.0683 MPa was located on the lingual apical area of U3, and the maximum compressive stress of -0.0909 MPa was at the lingual apex of U2.

In case 2, the stress level was higher than that of case 1 (Fig 5). S1 on the labial and lingual surface of U1 and U3 showed a similar trend as in case 1, but tensile stress concentration on the lingual apex of U3 increased. Most of the labial and lingual surfaces of U2 showed compressive stress, suggesting its bodily retraction and intrusion. Stress concentration area around lingual apex of U2 was enlarged dramatically. Maximum tensile stress increased to 0.0736 MPa while maximum compressive stress increased to -0.1161 MPa, and their locations almost remained the same.

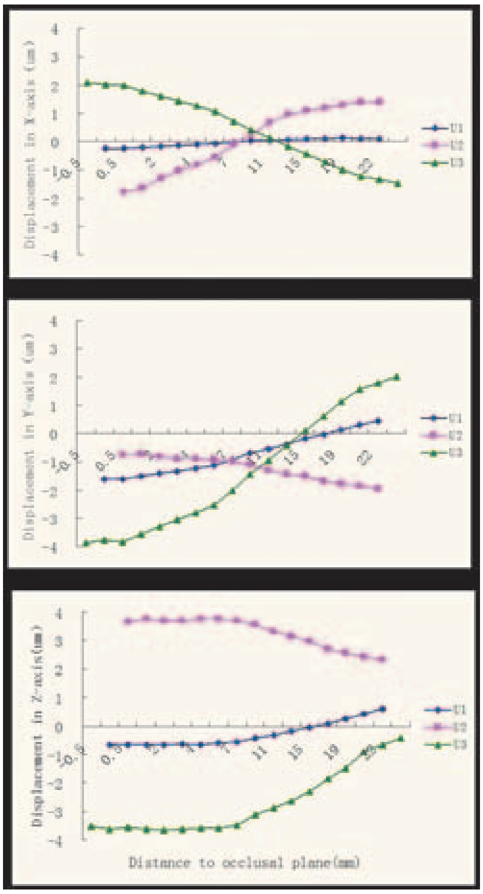

Fig 3 Displacement of each tooth in case 2 (U1, central incisor; U2, lateral incisor; U3, canine).

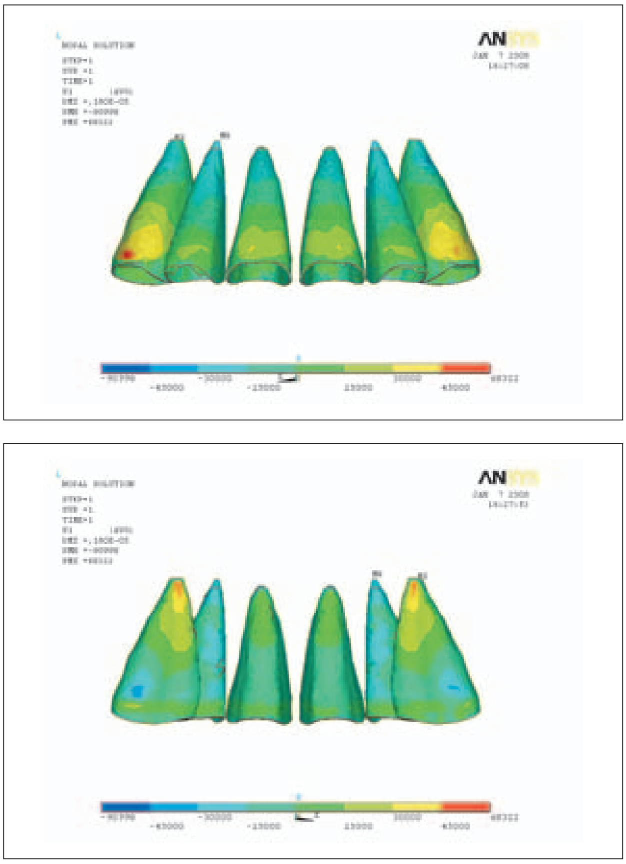

Fig 4 First/maximum principal stress (S1) distribution in periodontal ligament in case 1 (above, labial surface; below, lingual surface).

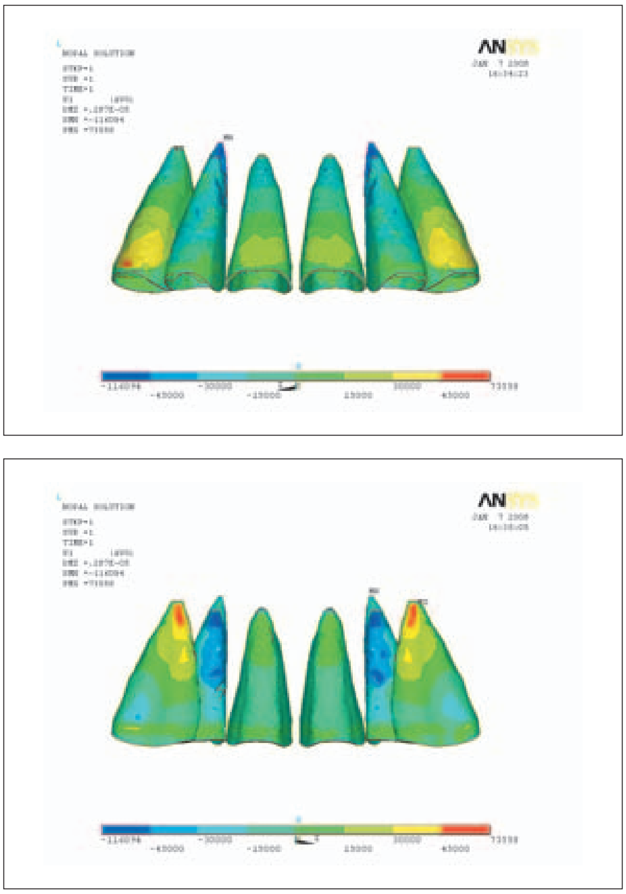

Fig 5 First/maximum principal stress (S1) distribution in periodontal ligament in case 2 (above, labial surface; below, lingual surface).

Discussion

Biomechanical simulation of this model

After semi-automatic processing of the cross-sectional images obtained from CT scan, a 3D FE model of six maxillary anterior teeth with preadjusted appliance was established. This model was highly realistic for simulation of orthodontic tooth movement such as anterior tooth retraction, as it represented intermaxillary bone with normal periodontal condition. Although there is clearance between the archwire and bracket slot in the clinic, it is quite difficult to simulate their dynamic contact relationship because of its small dimensions and unpredictable contact. In previous studies, link elements and spring elements have been used to link archwire and brackets, but their rigidity was unmeasurable and torque was not transferable through the mechanism[5,6]. During en masse retraction, six anterior teeth are in close contact with each other and relative displacements among them are limited. The objective of the present study was to investigate force distribution on each tooth and the resulting instant strain and stress. In this model, the archwire and brackets were merged together and force and torque can be transferred without any loss.

PDL is a biological soft tissue with intrinsic non-linear viscoelastic properties. Definitions of PDL's mechanical property would directly affect the accuracy of calculation because its Young's modulus is the lowest in this model and its deformation was greater than that of teeth and bone. Yoshida reported that elastic modulus of human PDL increased almost exponentially with the increment of load and its Young's modulus was about 0.69 to 0.96 MPa under 1.5 to 2.0 N orthodontic force[9]. To simplify the calculation, we designated PDL as a linear elastic material and assigned it the elastic modulus as 0.68 Mpa, which was adopted in several relevant studies[5,6].

Routine anterior teeth retraction using the sliding mechanism and its limitations

Case 1 simulated the routine procedure of anterior tooth retraction using a sliding mechanism. Retraction force in this direction was below the CRe of maxillary anterior teeth. According to traditional orthodontic biomechanics, maxillary anterior teeth should generate lingual crown tipping movements. In this simulation, archwire/bracket play was not taken into account. However, finite element analysis (FEA) results showed lingual crown tipping of U1 and U3 and controlled lingual crown tipping of U2, suggesting that rectangular archwire maintained the inclination of U2 to a certain degree, compared with round archwire. Differences between movements of U1 and U2 were due to archwire torsion between them. Therefore, archwire used for space closure should be rigid enough to maintain the dental arch form and the relative position of each tooth.

In practice, lingual crown tipping of anterior teeth is more obvious owing to archwire/bracket play. If the labial inclination of anterior teeth is higher than the normal value, this trend is advantageous for the final treatment result. However, when they are of normal inclination as in this model, orthodontists should employ reverse curve and/or gable bend, which generates an intruding force and lingual root torque to counteract the extruding and lingual crown tipping trend[2]. The degree of reverse curve and gable bend calls for further investigation. Another alternative is to increase the preadjusted torque in the U1 and U3 bracket slot.

When extra lingual root torque is applied on anterior teeth, their anchorage value will increase accordingly. Thus the anchorage of posterior teeth should be reinforced in accordance. However, in patients where maximum anchorage is needed, traditional methods to reinforce molar anchorage, such as transplatal arch, extraoral force, etc. are still unable to anchor posterior teeth. Therefore the conventional sliding mechanics is limited in maximum anchorage cases.

Anterior tooth retraction with force passing near the CRe of anterior teeth

Implants could provide absolute anchorage and be convenient for both patients and orthodontists. Park et al[1,2] reported successful en masse retraction of six anterior teeth with an anterior hook of 3 to 5 mm and an implant 8 to 10 mm gingival to bracket slots. They suggested that force in this configuration passed near the CRe of the segment, and their bodily retraction can be achieved after adding torque curve to the archwire. Case 2 simulated such a clinical procedure.

The anterior hook has been extensively used to change the direction of retraction force. However, a long hook is inconvenient for patients, so a 4.0-mm-long hook was used in the present study, which was clinically acceptable. In this case, the hook served as a level arm, and the generated positive torque (lingual root torque) passed through the archwire to each tooth. The vertical intrusive component force also increased the lingual root torque. This torque could counteract the lingual crown tipping and extrusion of maxillary anterior teeth to achieve lingual translation. However, bodily retraction and intrusion was observed only in U2, while U1 and U3 still showed lingual crown tipping movement. This can be explained as torque loss because of archwire torsion at the mesial and distal side of U2. Thus U1 and U3 were loaded with smaller positive torque than U2. In addition, the canine at the back of this segment bared most of the palinal retraction force. Torque transmitted to U3 was insufficient to counteract the trend of lingual crown tipping.

In practice, archwire twists in the U2 bracket slot according to the actual wire/bracket play, but U2 will still be loaded more by this force system than planned, which would be demonstrable as much higher stress levels and an expansion of area with stress concentration (over 0.045 Mpa) at its lingual surface. Stress concentration is considered as a major factor of root absorption. In an *in vivo* experiment by Hohmann, increased pressure in PDL correlated well with the location of root resorption of human teeth[10]. It is suggested that retraction force magnitude should be controlled and root resorption of U2 should be monitored during treatment.

In the *x*-axis, the different tipping trend of U2 and U3 may result from the transverse moment force of retraction force. This outward force moment passed through the hook to the archwire and produced opposing archwire deformation at U2 and U3. Torque at U2 made its root tip mesially, while torque at U3 caused its root to tip buccally. This phenomenon can be observed in practice. In some cases of en masse retraction with implant anchorage, we found that the root of the maxillary canine was obvious just under the gingival mucosa. The reason was that its root did not move lingually with its crown, or even moved buccally. Therefore, negative torque (–7 degrees) for maxillary canine may be inappropriate within this mechanism. Zero torque or even positive torque is better for the maxillary canine.

Relationship between direction of retraction force and CRe

In the *z*-axis, each anterior tooth showed a different movement trend: U2 was intruded, whereas U1 and U3 were extruded. The reason is that archwire did not have enough rigidity to maintain their original vertical position. Retraction force caused the anterior hook to bend backwards, the archwire mesial to it to bend upwards, and archwire distal to it to bend downwards.

Although initial displacements of each tooth varied, their long-term vertical movements will be concordant and are dependent on the relationship between the retraction force direction and the CRe. When the CRe is above the imaginary force line, clockwise rotation will be observed; when the CRe is below the imaginary force line, anti-clockwise rotation will be observed.

In our previous study using the same model, six maxillary anterior teeth blocked with 2×2 mm^2 SS archwire were subjected to horizontal retraction forces of 150 g at different levels[11]. The results showed that the labial-lingual displacements of incisors varied from lingual crown tipping to lingual translation, and controlled lingual root movement as the force level increased. When retraction force was 10 mm above the bracket slot, the maxillary incisors generated almost uniform lingual translation, and compressive stress on their lingual surface was similar in all cases. Although the canines did not achieve lingual translation in any of these cases, vertical location of CRe of maxillary anterior teeth is speculated to be 14 mm above the incisal edge of the central incisor. This is consistent with a study by Choy et al[12], which concluded that the CRe of the maxillary anterior segment was located 14.5 mm apical and 9.5 mm distal from the incisal edge of central incisors.

According to this assumption, the CRe was above the imaginary force line in case 2. FEA results of case 2 also suggest that force in this direction could not produce enough positive torque to achieve bodily retraction in cases of maxillary protrusion with normal labial inclination.

Park et al[1,2] managed several successful en masse retraction cases with 0.406 × 0.559-mm archwire, and the maxillary incisors showed well-controlled inclination to the Frankort-Horizontal (FH) plane after space closure. Their findings support the notion that retraction force passing close to the CRe can eliminate the necessity of lingual root torque to prevent lingual crown tipping, because 0.406 × 0.559-mm archwire in 0.559-mm brackets produced no torque on anterior teeth. The divergence of theoretical research and clinical results on archwire size, force direction and extra lingual root torque calls for further study. Comparisons between simulations of long-term orthodontic tooth movements and clinical treatment results of patients in the same situation may present a promising solution.

Conclusions

This FEM was highly realistic for simulation of orthodontic tooth movement. During routine anterior tooth retraction using sliding mechanics with plain archwire, the crown of each tooth tends to tip lingually. Force passing near the CRe of six anterior teeth makes their displacement and stress distribution more uniform, but their translation is still not detectable. Lateral incisors are loaded more than the other teeth and stress concentration at its lingual apex should be monitored. FEM could only calculate initial tooth displacement and stress distribution after force application. The biological and time-dependent reaction is still unpredictable and requires more clinical evidence.

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