Three-Dimensional Finite Element Analysis on En-Masse Retraction of the Maxillary Anterior Teeth With Quantitative Combined Loading Control

Hui Qie, MDS[1]
Lingliang Kong, MDS[2]
Fan Zhang, MDS[1]
Chenxi Li, MDS[1]
Lin Lu, MDS[1]
Chenlei Dou, MDS[1]
Lihua Shan, DDS[1]*

This study aims to elucidate the biomechanical effects of combined loading of maxillary anterior and posterior implants using the sliding method on en-masse retraction of the anterior teeth and to quantify the loading ratio (LR) of anterior and posterior implants to achieve controlled retraction of the maxillary anterior teeth. A three-dimensional finite element model of the maxilla-upper dentition appliance was constructed. Implants were placed on the distal (A) and mesial (B) sides of the lateral incisors as well as on the mesial (C) side of the first molar and different amounts of force were loaded between the implants using 2- or 5-mm traction hooks. The labiolingual movement of the anterior teeth was recorded and the relationship between the LR of the implants and the movement of the central incisors was evaluated. With 2-mm traction hooks, the central incisors exhibited a translation tendency during retraction at lower A/C and B/C LR and labial or lingual crown inclination at higher values. With 5-mm traction hooks, the central incisors, lateral incisors, and canine teeth exhibited a labial crown inclination. The results of this study suggest that 2-mm traction hooks can cause labial crown inclination, translation tendency during retraction, or lingual crown inclination of the central incisors due to alterations in the LR of the anterior and posterior implants. The central incisors only exhibited labial crown inclination during combined loading of the anterior and posterior implants when 5-mm traction hooks were used.

Key Words: three-dimensional finite element, implant anchorage, en-masse retraction, sliding method, translation movement

INTRODUCTION

Maxillary protrusion is a type of malocclusion commonly encountered in the clinic, often in combination with vertical overgrowth of the premaxillary bone. This combination results in a gummy smile,[1,2] which seriously affects the appearance of the patient. During orthodontic treatment, stable and reliable anchorage coupled with good anterior teeth control is essential for retraction of the anterior teeth and improvement of the facial esthetic.[3,4]

Implant anchorage can be performed to take maximum advantage of the extraction space, retract the anterior teeth, simultaneously control the vertical height of the posterior teeth well, and even intrude the posterior teeth.[1–3,5–7] However, after retracting the anterior teeth using implant anchorage, some issues may arise that can affect the treatment effect and the health of periodontal tissues.[8,9] Some scholars have studied the position of the center of resistance for anterior teeth required to achieve bodily retraction of the anterior teeth.[10,11] However, obvious individual differences exist in the position of the center of resistance of anterior teeth,[12–14] and the position changes during closure of the extraction space.

In recent years, three-dimensional (3D) finite element modeling has been widely employed in the study of oral biomechanics.[14–16] To achieve bodily retraction of the anterior teeth, many studies have compared the effect of different implant[15–18] and traction hook heights on the retraction of the anterior teeth.[16,18,19] Though the mechanical effects of a combination of multiple implants on retraction of the anterior teeth were investigated, the biomechanical characteristics of anterior teeth retracted with 4 implants have not been defined.[15,18]

Due to significant improvements in micro-implant morphology, implants can now be placed in the mesial alveolar ridge of the maxillary first molar, providing good anchorage for retraction of the anterior teeth.[2,6,8] A maxillary anterior implant can effectively intrude the anterior teeth, effectively solving the

[1] Department of Orthodontics, The Second Hospital of Hebei Medical University, Shijiazhuang, China.
[2] Department of Orthodontics, The Jining Hospital of Stomatology, Jining, China.
* *Corresponding author,* e-mail: selindashan@163.com
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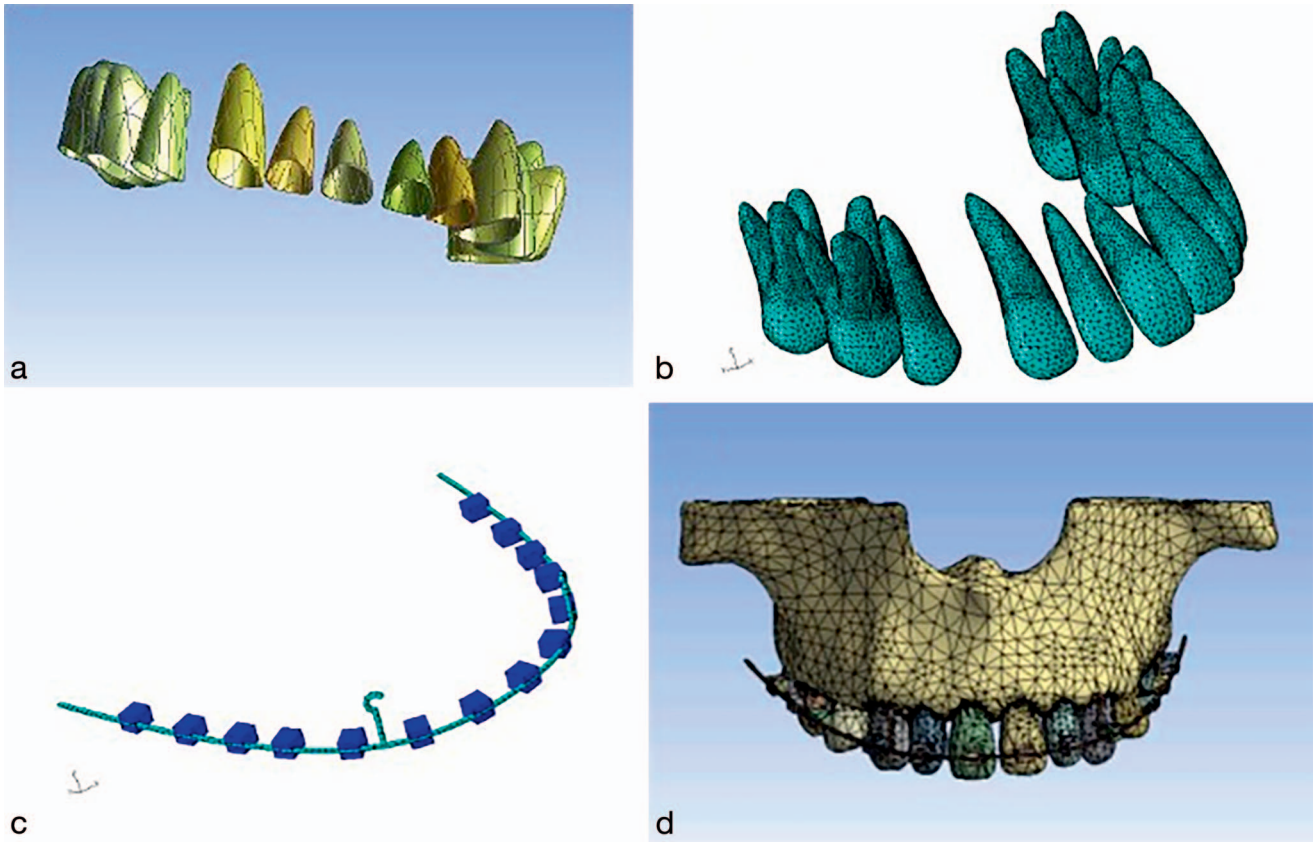


Figure 1. Construction of geometric model.

problem of a gummy smile. We hypothesized that during the process of closing the extraction space and retracting the anterior teeth, loading of the anterior teeth can be achieved through simultaneous loading of the anterior and posterior implants. The combined loading forces can pass through the center of resistance of the anterior teeth to achieve overall backward and upward movement of the maxillary dental arch and forward rotation of the mental region.

In this study, a model is simulated to simultaneously apply load to the maxillary anterior and posterior implants with different amounts of force, determine the labiolingual movement tendency of the anterior teeth, and explore the biomechanical characteristics of the anterior teeth retracted with the anterior and posterior anchorage implants. The goal is to provide a theoretical basis for effective control of anterior tooth movement following implant anchorage.

Materials and Methods

A spiral computerized tomography scan of the jawbone of an adult volunteer with a skeletal and dental Class II relationship and proper overjet and overbite occlusion was performed. The bone window was scanned with a screw pitch of 0.875 mm, layer thickness of 0.625 mm, and bed velocity of 0.5 mm/s. The maxillary bone was cross-sectionally scanned with reference to the Frankfort plane and parallel to the occlusal plane, and the results were stored in DICOM3 format. A solid model of the cortical bone, cancellous bone, tooth tissue, and periodontal ligament was established using the Mimics 10.1 (Materialise NV, Gent, Belgium), Geomagic 11.0 (3D Systems, Rock Hill, SC), and Catia V5 (Dassault Systèmes, Lyon, France) programs. The thickness of the periodontal membrane was set as 0.25 mm. According to the oriental preajusted appliance-KOSAKA guidelines and the data standard for the MBT straight wire bracket, a maxillary archwire with a size of 0.019 $\times$ 0.025 inches and a bracket with a groove of 0.022 were constructed. Additionally, to facilitate clinical judgment of the resultant direction of the retraction force and intrusion force, 2- and 5-mm traction hooks were attached to the archwire between the bilateral lateral incisors and canine teeth. ANSYS Workbench 13.0 (ANSYS, Inc, Canonsburg, Penn) software was used to create a 3D finite element model, as shown in Figure 1. The model was created using the Solid 187 entity unit-tolerant system in Workbench l3.0. To facilitate the calculation, the areas outside the periodontal membrane were divided automatically by the system. The model complex included 2 435 365 nodes and 1 798 348 Solid 187 entity units. Models of the upper dentition, maxillary bone, periodontal membrane, straight wire appliance, and archwire created in this study were independent of each other, and the upper dentition model was well-matched with the appliance and archwire. This study was approved by the Medical Ethics Committee of the Second Hospital of the Hebei Medical University.

In this study, the degrees of freedom for the maxillary crest and posterior nodes were completely constrained. The finite

Table 1

Mechanical properties of constituent materials

Material	Young's Modulus (MPa)	Poisson's Ratio
Tooth	2E4	0.30
Periodontal membrane	5.0	0.49
Alveolar bone	2E3	0.30
Bracket	2E5	0.30
Stainless steel	2E5	0.30

element mesh units of the dental roots, cortical bones, and periodontal membranes were connected by a common interface. It was assumed that there was no relative sliding among the straight wire appliances, teeth, and maxilla and that there was no relative sliding between the straight wire appliances and the teeth after loading. During the calculation, a binding constraint was used to constrain the teeth to the maxilla. To ensure the archwire was permanently constrained in the bracket groove, the "Banded" option in Workbench l3.0 was used to constraint both the teeth and maxilla. Long-term movement cannot be predicted from the original tooth movements. The elastic modulus and Poisson's ratio of the materials used in this study were based on the relevant literatures[10,18,20] and are presented in Table 1. The methodology was reviewed by an independent statistician.

Placement positions of the implants:

- Implant A: The space between the roots of the bilateral incisors and canine teeth, with a distance of 6 mm from the alveolar crest.
- Implant B: The space between the roots of the bilateral central incisors and the lateral incisors, with a distance of 6 mm from the alveolar crest.
- Implant C: The space between the roots of the bilateral second premolars and first molars, with a distance of 5 mm from the alveolar crest.
- Implant C was loaded with a force of 1 N to 2 N for retraction of the anterior teeth while implants A and B were loaded with a force of 0.50 to 1 N to intrude the upper anterior teeth.

The purpose of this study was to investigate the biomechanical properties of controlled retraction of the anterior teeth through combined loading of implants C and A or implants C and B. Implant C was loaded with forces of 1, 1.5, or 2 N, while implants A and B were loaded with forces of 0.50, 0.75, or 1 N. Traction hooks (2 or 5 mm) were attached to implants C and A, as well as to implants C and B, for combined loading (Figure 2). Implants A and B were combined with implant C to form 18 loading modes as shown in Tables 2 and 3. Using 2 traction hook heights, there were a total of 36 working conditions.

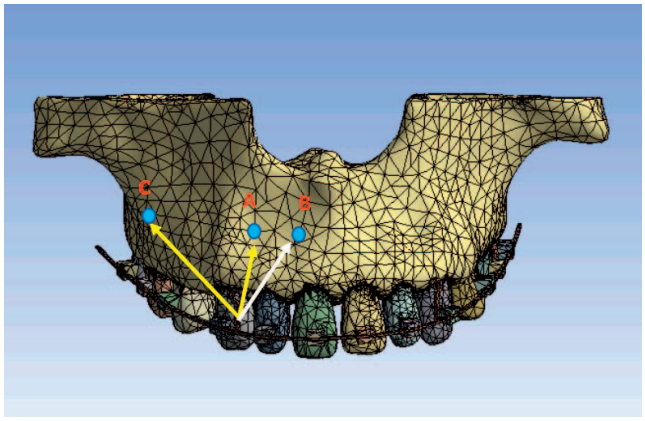


Figure 2. Schematic force diagram of implants A-C and implants B-C.

The rotation angle represents the instantaneous rotation tendency of the teeth after loading. In this study, the labiolingual rotation angles of the anterior teeth in the sagittal plane under various working conditions were calculated. Labial crown inclination was defined as a positive value, while lingual crown inclination was defined as a negative value. A crown inclination of zero indicated that there was no instantaneous rotation, and that bodily tooth retraction of the anterior teeth occurred under the loading condition.

Results

Effect of loading ratio of anterior and posterior implants

Two-millimeter traction hooks can adjust the movement mode of the central incisors by changing the loading ratio (LR) of the anterior and posterior implants according to the treatment purpose. When combined loading of implants A and C was performed with an A/C LR of 0.25 (such as in Case 3; A1: 0.50 N, B: −2 N), bodily tooth retraction of the central incisors occurred. Above 0.25, the higher the A/C LR was, the greater the labial crown movement tendency of the central incisors became. When combined loading of implants B and C was performed with B/C LR of 0.67 (such as in Case 17; B: −1 N, C: −1.50 N), bodily tooth retraction of the central incisors occurred. When the B/C LR exceeded 0.67, the central incisors exhibited labial crown movement, and higher ratios resulted in greater labial crown movement. When the B/C LR was less than 0.67, the

Table 2

Load values for implants A-C and B-C

Load Values of Implants		Implant A			Implant B		
		0.5 N	0.75 N	1 N	0.5 N	0.75 N	1 N
Implant C	1 N	Case 1	Case 4	Case 7	Case 10	Case 13	Case 16
	1.5 N	Case 2	Case 5	Case 8	Case 11	Case 14	Case 17
	2 N	Case 3	Case 6	Case 9	Case 12	Case 15	Case 18

TABLE 3

Combined loads values for implants A-C and B-C

Loading Values		Implant A			Implant B		
		0.5 N	0.75 N	1 N	0.5 N	0.75 N	1 N
Implant C	1 N	A50–C100	A75–C100	A100–C100	B50–C100	B75–C100	B100–C100
	1.5 N	A50–C150	A75–C150	A100–C150	B50–C150	B75–C150	B100–C150
	2 N	A50–C200	A75–C200	A100–C200	B50–C200	B75–C200	B100–C200

central incisors exhibited lingual crown movement and lower ratios resulted in greater lingual crown movement (Figure 3).

Effect of the magnitude of the loading force

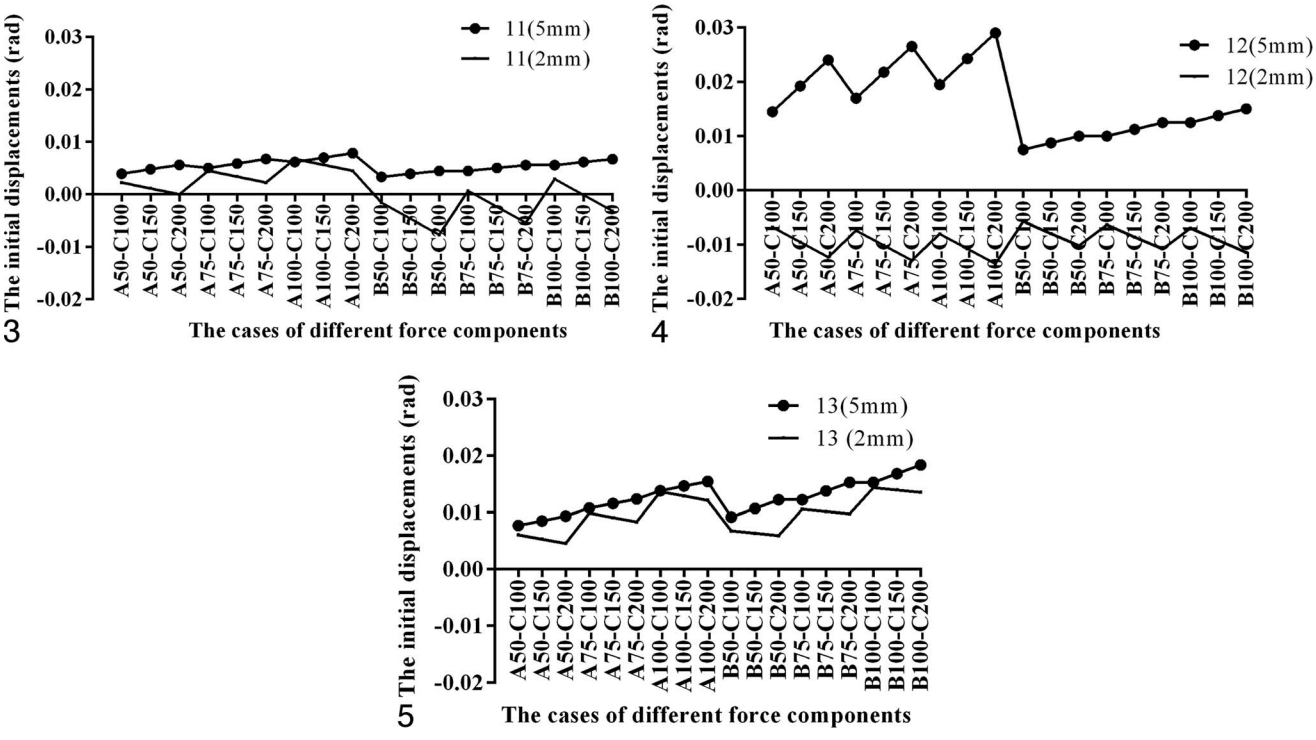
When 5-mm traction hooks were used to perform combined loading of the anterior and posterior implants, all anterior teeth exhibited labial crown inclination. When 2-mm traction hooks were used, the labial crown inclination tendency of the anterior teeth increased with the increase of the loading force applied to the anterior implants. The lingual crown inclination tendency of the anterior teeth increased with the increase of the loading force applied to the posterior implants, as shown in Figures 3 to 5.

Effect of the traction hook height

When 2-mm traction hooks were used, the central incisors exhibited labial crown inclination, bodily tooth retraction, or lingual crown inclination according to the loading mode used. Both lateral incisors exhibited lingual crown inclination while both canine teeth exhibited labial crown inclination. When 5-mm traction hooks were used, all central incisors, lateral incisors, and canine teeth exhibited labial crown inclination (Figures 3 through 5).

DISCUSSION

Maxillary protrusion and a gummy smile seriously affect the appearance of patients. Maxillary posterior and anterior implants are effective at improving the appearance of such patients. In this study, anterior teeth movement was controlled through combined loading of anterior and posterior implants. The purpose was to accurately control the movement of the anterior teeth in 3 dimensions according to the inclination angle and vertical height of the anterior teeth of the patient so



FIGURES 3–5. FIGURE 3. Initial displacements of the upper right central incisor (11) in the labial-lingual direction using archwire with 2- or 5-mm hooks under different loads cases (all results are expressed in rad). **FIGURE 4.** Initial displacements of the upper right lateral incisor (12) in the labial-lingual direction using archwire with 2- or 5-mm hooks under different loads cases (all results are expressed in rad). **FIGURE 5.** Initial displacements of the upper right canine (13) in the labial-lingual direction using archwire with 2 or 5 mm hooks under different loads cases (all results are expressed in rad).

as to realize counterclockwise rotation of the mandibular plane and forward rotation of the mental region to improve the facial shape of patients with maxillary protrusion. The results of this study showed that when 2-mm traction hooks were used and the LR of the anterior and posterior implants equaled 0.67 (B-C implant load) or 0.25 (A-C implant load), the central incisors exhibited bodily tooth retraction. When the loading force of anterior implants was increased, the labial crown inclination of the anterior teeth increased. When the loading force of the posterior implants was increased, the lingual crown inclination of the anterior teeth also increased. When 5-mm traction hooks were used, all central incisors, lateral incisors, and canine teeth exhibited labial crown inclination. We believe that the reason for the difference between the effects of the 2- and 5-mm hooks on the movement of the anterior teeth is that the combined force from intrusion and retraction with the 5-mm hook is higher than that with the 2-mm hook. Our results indicate that the combined force from intrusion and retraction is located near the center of resistance (CR) of the anterior tooth when the 2-mm hook is used, and the direction of the combined force can be changed by adjusting the value of the force. In contrast, with the 5-mm hook, the combined force from intrusion and retraction is always apical to the CR of the anterior tooth even if the force values are adjusted; hence the front tooth is always moving due to labial crown inclination.

In the process of closing the extraction space and retracting the anterior teeth, selective control of the movement of the teeth according to the specific situation is essential to achieve good results in patients with maxillary protrusion.[21] According to biomechanical knowledge, the relationship between the loading direction and the position of the center of resistance determines the movement direction of the object. To achieve bodily tooth retraction of the anterior teeth, some scholars recommend the use of long traction hooks for retraction of the anterior teeth with anchorage implants.[11,15,22] However, the insertion of long anterior traction hooks is uncomfortable for patients, and a better option is needed.[23] Moreover, long traction hooks have an obvious leverage effect, which is likely to deform the archwire, increase sliding friction, and affect the movement of the anterior teeth.[19] In addition, the position of the posterior mucogingival line limits the placement height of the implant, and the desired result of moving the maxillary dental arch toward the posterosuperior direction cannot be achieved by increasing the height of the anterior traction hooks. Another approach to change the direction of the action force line involves changing the placement height of the implant. A report by Chetan et al[17] showed that changing the vertical position of the implant has little effect on the movement mode of the anterior teeth. The position of the center of resistance for the anterior teeth has large individual differences and is related to the inclination degree of the anterior teeth, the height of the alveolar ridge, and the length and shape of the dental root. In addition, the position of the center of resistance for the anterior teeth may change with closure of the extraction space.[8,19,23] Therefore, it is clinically difficult to accurately determine the position of the center of resistance for the anterior teeth and to change the loading direction at any time according to the condition of the anterior teeth. For the aforementioned reasons, the position of the center of resistance was not calculated in this study. The aim of the study was to devise a simple method to achieve bodily movement during retraction of the anterior teeth using the LR. According to the inclination and overbite of the maxillary anterior teeth, vertical control of the anterior teeth was achieved by increasing or decreasing the LR.

After posterior implant anchorages are used to retract the anterior teeth in clinical practice, the anterior teeth are often too upright,[5,8,9,12,21] which affects the treatment results and the health of the periodontal tissues. The use of anterior implants can effectively intrude the anterior teeth and lead to lingual movement of the root apex, significant improvement of gummy smiles, and avoidance of problems such as anterior teeth that are too upright after closure of the extraction space. The loading force line can be easily controlled with combined loading of anterior and posterior implants. Further, with the improvement of implant morphology and the introduction of self-tapping implant technology, clinical micro-implant surgery has become much simpler. In 2017, Namburi et al[15] compared the effects of 3 implants and 9-mm traction hooks on retraction of the anterior teeth, reporting that placement of the implant in the area between the long traction hook and the maxillary central incisor is likely to cause discomfort to the patient. Sung et al[18] compared the effects of 2 and 4 implants on retraction of the anterior teeth with different implant heights and different traction hook heights. The results showed that after combined loading of 4 anterior and posterior implants with 2-mm traction hooks, 6 anterior teeth were slightly intruded and inclined in the labial direction, with no clear indication of how to flexibly control the retraction of the anterior teeth with 4 implants. We explored the biomechanical mechanisms of the retraction of the anterior teeth with 4 implants, so as to provide a simple alternative for controlled movement of the anterior teeth based on the inclination angle of the anterior teeth of the patient. The results of this study suggest that to realize bodily tooth retraction of the anterior teeth, 2-mm traction hooks should be selectively used with an LR close to 0.67 for the anterior and posterior implants (B-C) or close to 0.25 for implants A-C. If the anterior teeth are upright or introverted and are expected to develop simultaneous retraction and labial crown inclination, 5-mm traction hooks can be used to perform combined loading of the implants. Alternatively, 2-mm traction hooks can be used with an LR for implants B and C greater than 0.67 or an LR for implants A-C greater than 0.25.

During closure of the extraction space, the direction of the retraction force and the intruding force changes, altering the combined force direction. Thus, during each follow-up visit, the LR should be adjusted according to the inclination and overbite of the anterior teeth. If the overbite of the anterior teeth is too deep or the torque of the upper anterior teeth is lost, the vertical force should be increased or the retraction force should be reduced, that is, a force of A/C LR $>$ 0.25 load or B/C LR $>$ 0.67 load can be applied. On the contrary, if the anterior teeth are inclined too far or exhibit a tendency to open, the retraction force should be increased, that is, B/C LR $<$ 0.67 load or 5-mm traction hook load should be adopted. The intrusion effect is also important during retraction of the anterior teeth in cases of maxillary protrusion combined with vertical overgrowth. To obtain more effective intrusion during anterior tooth retraction,

vertical loading should be increased, that is, the 2-mm traction hook should be loaded with A/C LR $>$ 0.25 or B/C LR $>$ 0.67. Although the higher hook can be close to the CR, due to the uncertain position of the CR of the anterior teeth in each patient and the change of CR with the retraction of the anterior teeth, a single and constant loading direction cannot meet the treatment needs for different tilt angles of the anterior teeth. Anterior implants are known to exert a force on the anterior teeth, but how the anterior and posterior implants are loaded has not been reported in the literature. This study provides a simple method to change the movement mode of the anterior teeth at any time according to the degree of inclination of the anterior teeth and the facial shape of the patient, which will be helpful in selecting the ideal loading mode during the process of anterior teeth retraction.

Only the initial tooth movement was calculated in this study. To simulate the long-term orthodontic movement, repeated calculations were performed,[24] but the simulation was not consistent with the actual clinical tooth movement. According to Upadhyay et al,[22] the tooth movement after implant loading is divided into 4 phases: the unsteady state, controlled state, restorative phase, and continuous/heavy force. Because of the play of the archwire-bracket, the early movement of the incisors was characterized by tipping and the wire was deflected, which resulted in restoration of the incisors. The systematic review by Xu and Xie[5] showed that even with the use of a long hook, the incisors were still too upright after the spaces were closed and vertical control of the incisors was insufficient. This indicates that the root movement caused by archwire deformation cannot meet the clinical demand because the stainless steel wire used in the clinical setting has a certain elasticity and insufficient rigidity, which makes it difficult to generate sufficient third-order torqueing of the incisors. Another reason is that the CR of the anterior teeth changes constantly during the process of retraction, making it difficult to accurately simulate the action of long-term orthodontic movement. Although this experiment was only focused on the initial displacement of the incisors after implant loading, it provided the loading ratio for the mini implants, so that the clinicians could flexibly adjust the loading according to the actual condition of the front teeth during each revisit to achieve controlled tooth movement.

Some differences were observed between the results obtained using the 3D finite element method and the results obtained in clinical practice. The relationship between the resultant force direction of anterior and posterior implants and the center of resistance of the implant is complex and has individual differences in 3D space, which requires further study.

Conclusion

Based on the results of this study, we believe that the use of 2-mm traction hooks can cause labial crown inclination, bodily tooth retraction, and lingual crown inclination of the central incisors due to changes in the LR of anterior and posterior implants. When 5-mm traction hooks are used to perform combined loading of anterior and posterior implants, the central incisors only exhibit labial crown inclination.

Abbreviations

CR: center of resistance
LR: loading ratio

Acknowledgments

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Note

The authors declare that they have no conflict of interest.

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