AJO-DO

Finite element analysis of the effect of power arm locations on tooth movement in extraction space closure with miniscrew anchorage in customized lingual orthodontic treatment

Yi Feng,[a] Wei-Dong Kong,[a,b] Wan-Jing Cen,[a] Xue-Zhong Zhou,[c] Wu Zhang,[a] Qin-Tao Li,[d] Hai-Yuan Guo,[e] and Jian-Wen Yu[e]
Guangzhou and Foshan, China

Introduction: More patients are choosing customized orthodontic appliances because of their excellent esthetics. It is essential that clinicians understand the biomechanics of the tooth movement tendency in customized lingual orthodontics. This study aimed to evaluate the tooth movement tendency during space closure in maxillary anterior teeth with the use of miniscrew anchorage in customized lingual orthodontics with various power arm locations. **Methods:** Three-dimensional finite element models of the maxilla were created with miniscrews and power arms; the positions were varied to change the force directions. A retraction force (1.5 N) was applied from the top of the miniscrews to the selected points on the power arm, and the initial displacements of the reference nodes of the maxillary teeth were analyzed. **Results:** After applying force in different directions, power arms located at the distal side of the canines led to larger initial lingual crown tipping and occlusal crown extrusion of the maxillary incisors compared with power arms located at the midpoint between the lateral incisors and canines, and caused a decreasing trend of the intercanine width. **Conclusions:** In customized lingual orthodontic treatment, power arms located at the distal side of the canines are unfavorable for anterior teeth torque control and intercanine width control. Power arms located at the midpoint between the lateral incisors and canines can get better torque control, but still cannot achieve excepted torque without extra torque control methods, no matter whether its force application point is higher than, lower than, or equal to the level of the top of the miniscrews. (Am J Orthod Dentofacial Orthop 2019;156:210-9)

In the early 1970s, the first-generation lingual orthodontic appliance was developed by Kurz,[1] and the lingual mushroom-shaped archwire was put forward by Fujita.[2] In the early 1980s, lingual orthodontics was welcomed by many patients owing to its excellent aesthetics. However, because of the limitations of the appliance and the shortcomings of the lingual orthodontic technique, lingual orthodontics stagnated in the late 1980s. In 2001, Wiechmann pioneered the first customized lingual orthodontic system using computer-aided design/computer-aided manufacturing technology.[3] A customized lingual orthodontic system can effectively overcome the disadvantages of poor bracket positioning, inaccurate bracket rebonding, imprecise wire shaping, and difficult teeth adjustment of the traditional lingual orthodontic system, thus promoting the revival of lingual orthodontics. In clinical practice, the 6 anterior teeth can be retracted as a unit in lingual orthodontic

[a]Department of Orthodontics, First Affiliated Hospital of Jinan University, Guangzhou, China.
[b]Department of Orthodontics, School of Stomatology, Jinan University, Guangzhou, China.
[c]Foshan Stomatology Hospital, School of Stomatology and Medicine, Foshan University, Foshan, China.
[d]Suihua Dental Hospital, Jinan University, Guangzhou, China.
[e]Technicians, Riton Biotechnology Company, Guangzhou, China.
Yi Feng and Wei-Dong Kong are joint first authors and contributed equally to this work.
All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest, and none were reported.
Funding: Science and Technology Planning Project of Guangdong Province, China (grants 2015A020214015, 2016A020220015).
Address correspondence to: Wei-Dong Kong, Department of Stomatology, First Affiliated Hospital of Jinan University, No 613 Huangpu Avenue, Guangzhou 510630, China; e-mail, wdkong@sina.cn.
Submitted, December 2017; revised and accepted, August 2018.
0889-5406/$36.00

https://doi.org/10.1016/j.ajodo.2018.08.025

treatment, so the anchorage control is one of the keys to successful treatment. Using miniscrews to retract maxillary anterior teeth in customized lingual orthodontic treatment can effectively provide additional skeletal anchorage and achieve maximal en masse retraction of the anterior teeth.[4] However, different directions of the retraction force will cause different movement patterns of the anterior teeth during extraction space closure, which may be helpful or unfavorable to achieve the treatment goals. Therefore, it is essential to understand the biomechanical mechanisms of the movement tendencies of the maxillary anterior teeth during retraction with the use of miniscrews in customized lingual orthodontics.

Three-dimensional (3D) finite element analysis, an effective computer simulation technique, is widely used to simulate orthodontic force application and predict the biomechanical behavior of teeth.[5-7] In the present study, 3D finite element models including teeth, periodontal ligament, alveolar bone, and customized lingual orthodontic system were established. The purpose of this study was to analyze the movement tendencies of the teeth when the power arms are located at different positions, and the force application points on the power arm at different heights, thereby providing valuable information for clinical application of the customized lingual orthodontic technique.

MATERIAL AND METHODS

One healthy adult orthodontic patient was selected as the subject of this study. The selection criteria were as follows: permanent dentition, bilateral maxillary first premolar extraction, completed alignment and leveling, normal tooth morphology and symmetric arch, without dental caries, periodontal disease, or tooth loss, and without previous orthodontic treatment. Cone-beam computed tomography (CBCT) was used to obtain the patient's maxillary scanning image, and the scan slice thickness was 0.15 mm. The study was approved by the ethics committee of the First Affiliated Hospital of Jinan University (number 2018026). The CBCT image was stored in the standard digital imaging and communications in medicine (DICOM) format and then imported into Mimics 14.11 software (Materialise) to obtain the complete 3D geometric surface model of maxilla and maxillary dentition. The soft tissues were removed by threshold segmentation with the use of this software. Threshold segmentation, based on gray value, can separate different tissues with different gray values from the CBCT image easily. The obtained model was imported into reverse computer-aided design software (Geomagic Studio 13; Raindrop) to be transformed into a surface model. After smoothing, a smooth surface model of maxilla and maxillary dentition was obtained. To form a periodontal ligament structure with a uniform thickness of 0.2 mm, the whole dentition was expanded outward 0.2 mm evenly.[4,8-10]

Table I. Slot size of the customized lingual brackets (mm)

Measure	*Anterior teeth*	*Premolar*	*First molar*	*Second molar*
Mesiodistal distance	2.40	2.40	4.00	3.50
Labiolingual distance	0.46	0.80	0.80	0.50
Occlusogingival distance	0.80	0.64	0.64	0.80

A 0.018 × 0.025-inch lingual appliance, archwires, power arms and miniscrews were drawn by Pro/Engineer Wildfire 5.0 software (PTC). The appliance was a fully customized bracket with an anterior vertical slot and posterior horizontal slot. The bracket base and the lingual tooth surface fit completely. The bracket sizes are given in Table I, and the solid models of the brackets are shown in Figure 1. The archwire is a 0.017 × 0.025-inch mushroom-shaped ribbon stainless steel wire. The power arm, which was located at the midpoint between the lateral incisors and the canines or the distal side of the canines, extended toward the gingiva and then along the palate mucosa (Figs 2, *B* and 3, *B*). The distance between the palate mucosa and the power arm was ~0.5 mm. The miniscrew, which was located between the first molar and the second molar, was constructed with the following parameters (Ormco VectorTAS orthodontic implant): total length of the miniscrew, 10.7 mm; length of the part that implanted in the bone, 8 mm; vertical distance between the top of the miniscrew and the archwire plane, 8 mm.

The constructed maxilla, maxillary dentition, periodontal ligament, customized lingual brackets, archwire, power arms, and miniscrews were imported into Ansys Workbench 15.0 software to generate 3D finite element model. Automated mesh generators with manual controls were used. The archwire was regular in shape, so it was meshed with the use of tetrahedral elements. The tooth, bracket, miniscrew, and periodontal ligament were meshed with the use of hexahedral elements. As a mesh is made finer and the element count increases, the computation time also increases. The alveolar bone was meshed with the use of tetrahedral elements to optimize the computation time. The meshing convergence of the finite element models were tested before the analyses. A total of 2 models were established according to varied locations of the power arms: (A) power arms located at the midpoint between the lateral incisors

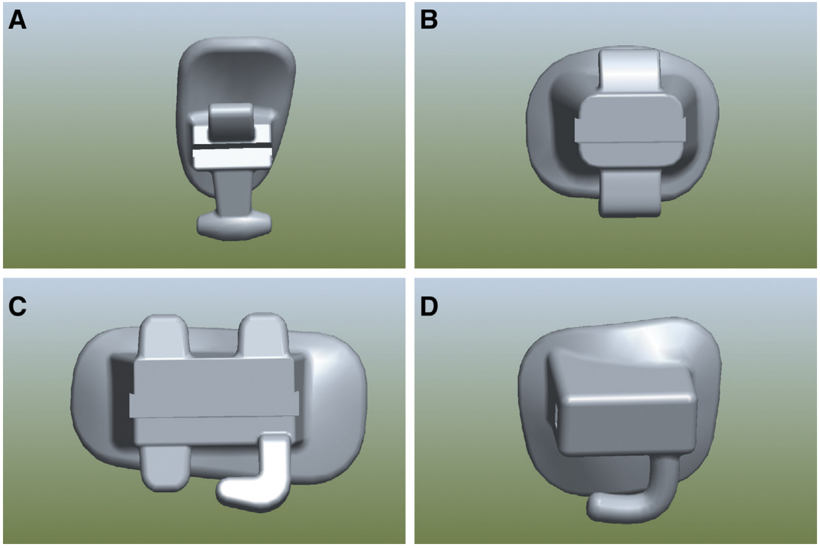

Fig 1. Customized lingual brackets models. **A,** Anterior tooth bracket; **B,** premolar bracket; **C,** first molar bracket; **D,** second molar lingual tube.

and the canines and the miniscrews located between the first molar and the second molar, of which the vertical distance from the archwire plane was 8 mm (Fig 2); (B) power arms located at the distal side of the canines and the miniscrews located between the first molar and the second molar, of which the vertical distance from the archwire plane was 8 mm (Fig 3). Model A comprised a total of 308,134 elements, which was the approximate number in model B as well.

There are 8 homogeneous and isotropic linear elastic materials, including cortical bone, cancellous bone, tooth, periodontal ligament, bracket, archwire, power arm, and miniscrew.[11,12] The material properties given in Table II were taken from a previous study.[9]

The upper part of the maxilla was set as the boundary region in which the elements were limited to move, so that the maxilla remained absolutely fixed when the force was loaded. After force loading, there was a sliding relationship between the brackets and the archwire without vertical separation, but there was no relative sliding between the teeth and the maxilla and between the brackets and the teeth. Points with vertical distances from the archwire plane of 6 mm, 8 mm, and 10 mm on the power arms in models A and B were selected as the force application points. A retraction force of 1.5 N was applied from the top of the miniscrews to the selected points on the power arm. The initial sagittal, transverse, and vertical displacement of the reference nodes of the maxillary teeth caused by the retraction force were measured according to the visualization results of the 3D initial teeth movements (Fig 4).

RESULTS

When the power arms were located at the midpoint between the lateral incisors and canines with the miniscrews located between the first molar and the second molar, after applying 1.5 N retraction force the maxillary central incisors showed tendencies of lingual crown tipping and labial root tipping, and these tendencies decreased as the vertical distance between force application points on the power arm and the archwire plane increased from 6 mm to 10 mm. The maxillary canines showed tendencies of lingual crown tipping and labial root tipping, and these tendencies increased as the vertical distance between the force application points on the power arm and the archwire plane increased (Table III).

When the power arms were located at the distal side of the canines with the miniscrews located between the first molar and the second molar, after applying 1.5 N retraction force the maxillary central incisors and canines showed tendencies of lingual crown tipping and labial root tipping, and these tendencies increased as the vertical distance between the force application points on the power arm and the archwire plane increased. Compared with power arms located at the midpoint between the lateral incisors and canines, the maxillary central incisors showed much more tendency of lingual crown tipping and labial root tipping when the power arms were located at the distal side of the canines (Table III).

When the power arms were located at the midpoint between the lateral incisors and canines with

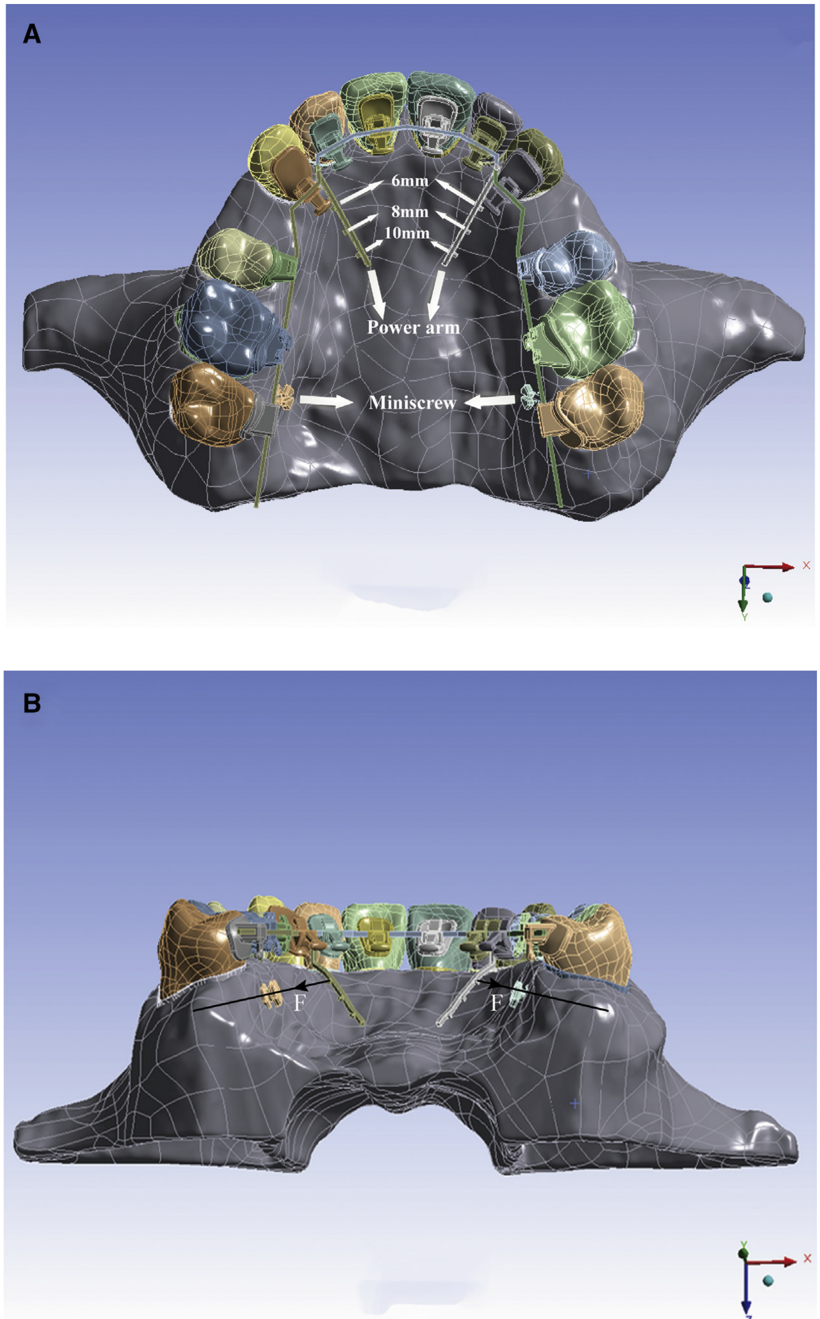

Fig 2. 3D finite element method model of the maxilla with power arms located at the midpoint between the lateral incisors and the canines, and miniscrews located between the first molar and the second molar, with vertical distance from the archwire plane of 8 mm. The upper part of the maxilla was set to be fixed. **A,** Occlusal view. Points at vertical distances from the archwire plane of 6 mm, 8 mm, and 10 mm on the power arms were selected as the force application points. A retraction force (1.5 N) was applied from the top of the miniscrews to the selected points on the power arm. **B,** Posterior view. The power arm extended toward the gingiva and then along the palate mucosa. The distance between the palate mucosa and the power arm was ~0.5 mm. The load vector (F) was from the top of the miniscrew to the selected point on the power arm.

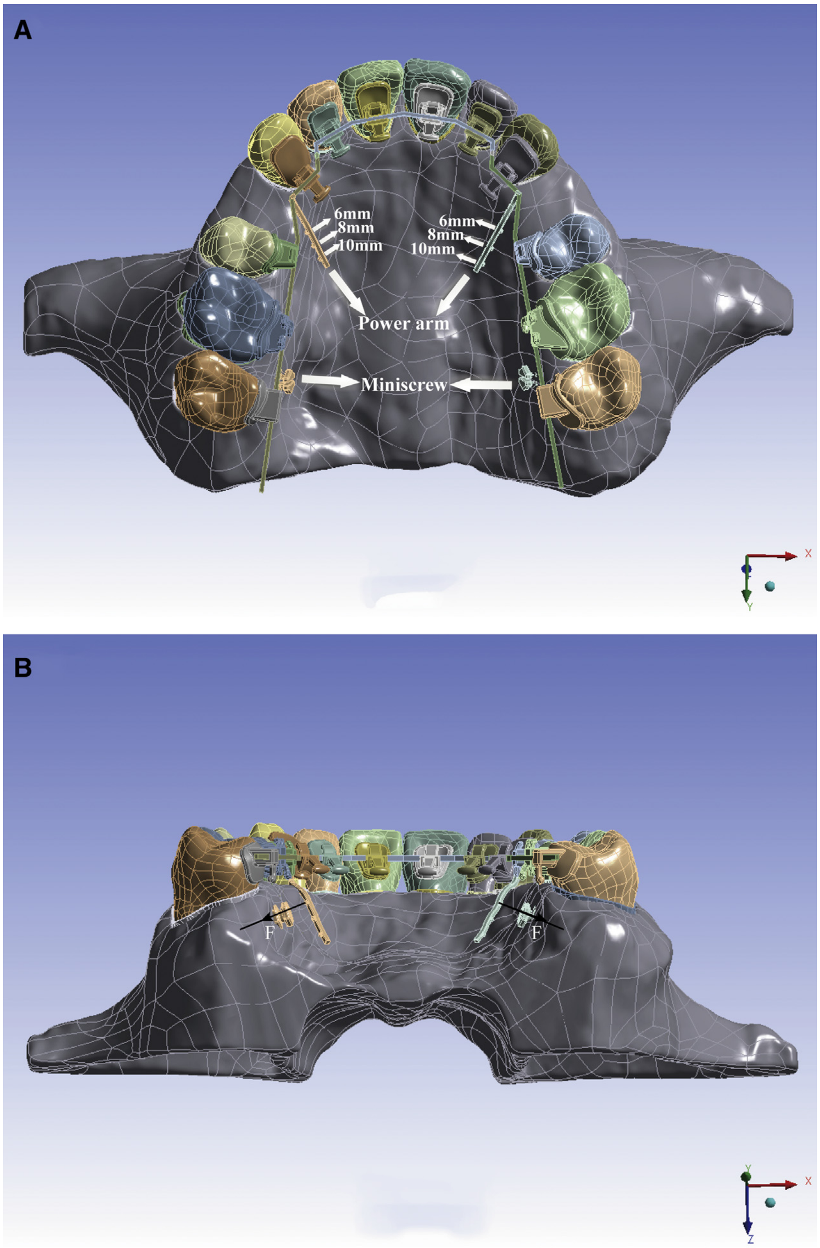

Fig 3. 3D finite element method model of the maxilla with power arms located at the distal side of the canines, and miniscrews located between the first molar and the second molar, with vertical distance from the archwire plane of 8 mm. The upper part of the maxilla was set to be fixed. **A,** Occlusal view. Points at vertical distances from the archwire plane of 6 mm, 8 mm, and 10 mm on the power arms were selected as the force application points. A retraction force (1.5 N) was applied from the top of the miniscrews to the selected points on the power arm respectively. **B,** Posterior view. The power arm extended toward the gingiva and then along the palate mucosa. The distance between the palate mucosa and the power arm was ~0.5 mm. The load vector (F) was from the top of the miniscrew to the selected point on the power arm.

Table II. Material properties

Material	Young modulus (GPa)	Poisson ratio
Cortical bone	13.4	0.30
Cancellous bone	7.8	0.30
Tooth	20.3	0.30
Periodontal ligament	0.05	0.49
Brackets, wire, power arm	205.9	0.30
Miniscrew	103	0.33

the miniscrews located between the first molar and the second molar, after applying 1.5 N retraction force the maxillary central incisors showed a decreasing occlusal crown extrusion trend and increasing apical root intrusion trend, and the canines showed an increasing apical root intrusion trend as the vertical distances of the force application points on the power arm from the archwire plane increased from 6 mm to 10 mm (Table IV).

When the power arms were located at the distal side of the canines and the miniscrews were located between the first molar and the second molar, after applying 1.5 N retraction force the maxillary central incisors and canines showed an increasing occlusal crown extrusion trend as the vertical distances of the force application points on the power arm from the archwire plane increased (Table IV).

When the power arms were located at the midpoint between the lateral incisors and canines with the miniscrews located between the first molar and the second molar, after applying 1.5 N retraction force the width of bilateral maxillary canines, second premolars, first molars, and second molars showed increasing trends that were increased as the vertical distance between the force application points on the power arm and the archwire plane increased from 6 mm to 10 mm (Table V).

When the power arms were located at the distal side of the canines and the miniscrews were located between the first molar and the second molar, the width of bilateral second premolars, first molars, and second molars showed increasing trends that were increased as the vertical distance between the force application points on the power arm and the archwire plane increased, whereas the intercanine width showed a decreasing trend under different force directions (Table V).

DISCUSSION

In theory, the anchorage value in lingual orthodontics is greater than in labial orthodontics, because the force acting on the anterior teeth passes through the lingual side of the center of resistance of the anterior teeth in lingual orthodontics and produces a lingual crown torque to the anterior teeth and a distal uprighting force on the posterior teeth throughout the retraction process, which increases the anchorage value of the molars.[13,14] However, Lawson[15] suggested that there was no difference of anchorage requirement between lingual and labial orthodontics in clinical practice. The anchorage control is the key to successful labial and lingual orthodontics, and the loss of anchorage will lead to poor treatment results. Many clinical practices have shown that miniscrew anchorage in lingual orthodontic treatment can attain effective anchorage control and achieve good treatment results.[16] In the retraction system composed of the miniscrews and the lingual power arms, different lengths and different positions of the miniscrews and the power arms will lead to different teeth and dentition movement patterns.[17]

When implanting the miniscrew, there is a risk of root proximity.[18] Improper placement of miniscrew would cause irreversible damage to the root. If the distance of the miniscrew site from the root surface is too small, the miniscrew would touch the root when the teeth moved during orthodontic treatment.[19] In clinical practice, the palatal miniscrew is usually implanted at the greater interradicular space between the posterior teeth, which reduces the risk of root injury during the implantation of the miniscrews. Poggio et al[20] found that on the palatal side, both the mesiodistal and buccolingual interradicular spaces between the first molar and second molar measured at 5 mm from the alveolar crest were largest, so the safest sites for implanting miniscrews were the interradicular spaces between the first molar and second molar, 5 mm from the alveolar crest on the palatal side. In the present study, the tendencies of teeth movement after applying retraction force were analyzed when the force application points on the power arm were lower than, higher than, or equal to the height of the miniscrews. In the finite element models of this study, the vertical distance of the miniscrew from the archwire plane is 8 mm. In this position, the vertical distance of the miniscrew located between the first molar and the second molar from the alveolar crest was 5.04 mm, which conformed to the principle of safety in clinical treatment.

In lingual orthodontics, because the lingual archwires have mushroom-shaped curves at the distal side of the canines, the 6 anterior teeth should be en masse retracted in the phase of space closure, instead of moving the canines to the right place first, followed by retracting the 4 incisors.[21] In addition, the space between the lateral incisor and canine should be avoided because of the high esthetic requirement of patients with lingual orthodontic treatment.[22] In tooth extraction cases of lingual orthodontics, the loss of torque

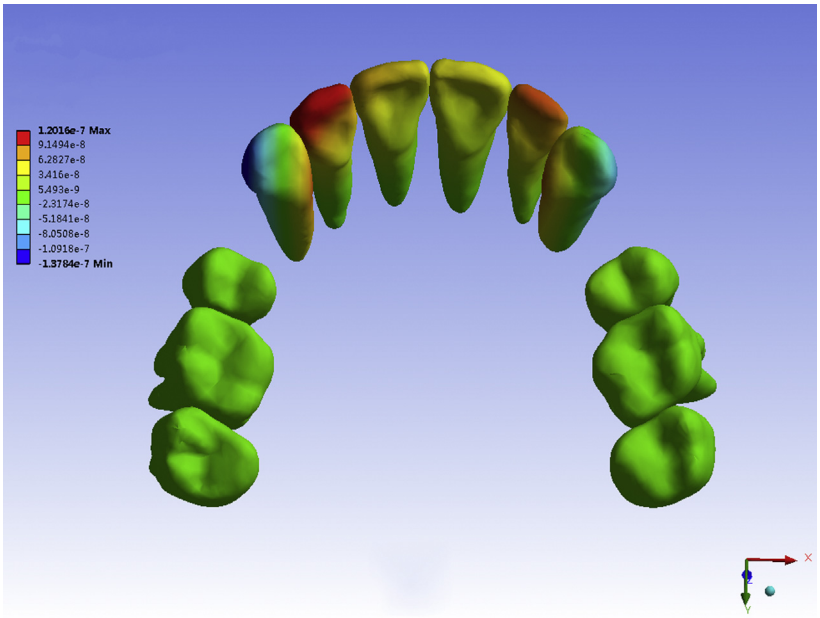

Fig 4. Example screenshot of the visualization results of the 3D initial teeth movements. The color scale shows the data distributions of the initial movements of the teeth under the retraction force, where each color corresponds to a range of values (unit = $\times 10^{-8}$ m). These visualization results were provided by the finite element analysis software. The initial sagittal, transverse, and vertical displacement values of the reference nodes of the maxillary teeth caused by the retraction force could be measured by the finite element analysis software.

Table III. Sagittal initial displacements of selected nodes of the maxillary teeth under the application of 1.5 N retraction force (unit = $\times 10^{-8}$ m)

Power arm		*Maxillary central incisor*			*Maxillary canine*		
Position	*Vertical distance to archwire plane*	*Crown*	*Root*	*Crown-root*	*Crown*	*Root*	*Crown-root*
Midpoint between lateral incisor and canine	6 mm	3.44	−1.02	4.46	−10.89	0.96	−11.85
	8 mm	2.37	0.02	2.35	−26.38	3.07	−29.45
	10 mm	1.17	1.10	0.07	−41.50	5.09	−46.59
Distal to canine	6 mm	4.13	−1.47	5.60	10.15	−1.28	11.43
	8 mm	4.78	−1.65	6.43	16.08	−2.22	18.30
	10 mm	5.68	−1.91	7.59	22.60	−3.25	25.85

Selected nodes: the midpoint of the facial axis of the clinical crown and the root apex. Values indicate the average initial displacements of selected nodes of the left and right maxillary teeth with the same name. + values indicate lingual displacements; − values indicate labial displacements.

control is likely to occur during the anterior teeth retraction phase, resulting in the vertical bowing effect including excessive lingual inclination of the maxillary incisors.[15,17] Liang et al[7] showed that the movement type of the maxillary incisor was crown lingual tipping in lingual orthodontics and was bodily translation in labial orthodontics under the same load in a 3D finite element analysis. In the present study, when the power arms were located at the distal side of the canines and the miniscrews were located between the first molar and the second molar, after applying 1.5 N retraction force the incisors showed lingual crown tipping and labial root tipping tendencies whether the vertical distance between the force application points on the power arm and the archwire plane was 6 mm, 8 mm, or 10 mm. The lingual crown tipping and labial root tipping tendencies of the incisors with the power arms located at the distal side of the canines were much more than

Table IV. Vertical initial displacements of the maxillary teeth under the application of 1.5 N retraction force (unit = $\times 10^{-8}$ m)

Power arm			
Position	*Vertical distance to archwire plane*	*Maxillary central incisor*	*Maxillary canine*
Midpoint between lateral incisor and canine	6 mm	1.84	−4.16
	8 mm	0.36	−11.29
	10 mm	−1.32	−18.01
Distal to canine	6 mm	2.64	2.05
	8 mm	3.01	4.14
	10 mm	3.51	6.40

Selected nodes: the midpoint of the facial axis of the clinical crown of the maxillary central incisor and canine. Values indicate the average initial displacements of selected nodes of the left and right maxillary teeth with the same name. + values indicate occlusal displacements; − values indicate apical displacements.

Table V. Transverse initial displacements of selected nodes maxillary teeth under the application of 1.5 N retraction force (unit = $\times 10^{-8}$ m)

Power arm					
Position	*Vertical distance to archwire plane*	*Maxillary canine*	*Maxillary second premolar*	*Maxillary first molar*	*Maxillary second molar*
Midpoint between lateral incisor and canine	6 mm	12.61	0.10	0.11	0.27
	8 mm	26.68	0.92	0.44	0.32
	10 mm	40.25	1.8	0.78	0.35
Distal to canine	6 mm	−5.99	8.45	3.21	0.95
	8 mm	−10.48	15.12	5.64	1.03
	10 mm	−15.35	22.69	8.40	1.12

Selected nodes: the cusp of the maxillary canine, the central fossa of the maxillary second premolar, first molar, and second molar. Values indicate the average initial displacements of selected nodes of the left and right maxillary teeth with the same name. + values indicate displacements away from the median palatine suture; − values indicate displacements toward the median palatine suture.

with the power arms located at the midpoint between the lateral incisors and canines. When the power arms were located at the midpoint between the lateral incisors and canines, with the miniscrews located between the first molar and the second molar, after applying 1.5 N retraction force the tendencies of lingual crown tipping and labial root tipping of the maxillary central incisors decreased as the vertical distance between force application points on the power arm and the archwire plane increased from 6 mm to 8 mm and then to 10 mm. The tendencies of labial crown tipping and lingual root tipping of the maxillary canines increased as the vertical distance between force application points on the power arm and the archwire plane increased. Therefore, it is necessary to preset the torque specifically when designing the brackets slots and bending the archwires to achieve effective torque control during the orthodontic treatment.

Stamm et al[23] found that 10° of changes of the anterior teeth torque will lead to 1.2 mm of changes in vertical distance, which has a significant effect on the esthetics in anterior teeth. In the present study, When the power arms were located at the midpoint between the lateral incisors and canines, with the miniscrews located between the first molar and the second molar, after applying 1.5N retraction force the maxillary central incisors showed a decreasing occlusal crown extrusion trend and increasing apical root intrusion trend, and the maxillary canines showed an increasing apical root intrusion trend as the vertical distances of the force application points on the power arm from the archwire plane increased; these were consistent with the sagittal trends. The changes of the anterior teeth torque led to changes in vertical distance, and this was also the case when the power arms were located at the distal side of the canines. Thus, good anterior teeth torque control is beneficial to the vertical control of the anterior teeth, which is conducive to the esthetics.

Before the advent of the miniscrew, headgear was used to increase the anchorage in lingual orthodontics.

When using headgear, the maxillary first molars are subjected to distal rotation force throughout the retraction process, so the width between the bilateral maxillary second premolars is easy to be widened and the width between the bilateral maxillary second molars is easy to narrow; this phenomenon is called transverse bowing effect. However, there is no such problem in lingual orthodontics with miniscrew anchorage. In the present study, the width between the bilateral maxillary second molars showed no narrowing trend, no matter if the power arms were located at the midpoint between the lateral incisors and canines or at the distal side of the canines, and no matter if the force application points on the power arms were lower than, higher than, or equal to the level of the force application points of the miniscrews. However, when the power arms were located at the distal side of the canines, the intercanine width showed a decreasing trend, which again indicated that the power arms located at the distal side of the canines were unfavorable for tooth movement control.

There are some limitations in this study. The finite element analysis was conducted in vitro, which cannot simulate factors such as play and torsion of the archwire within the slot. However, studies aiming at clinically indicating the tooth movement tendency in vivo are not feasible. Computer-based numeric simulation is the best option to apply biomechanical forces and predict the trend of tooth movement at the moment. This study reflects the trend of tooth movement under different directions of the retraction force, providing some references for clinical treatment planning. Future studies should focus on clinical assessment to verify the results of the finite element analysis. Moreover, further studies using the finite element method considering not only initial but also continuous tooth displacement would help to solve complex biomechanical problems in orthodontics.

CONCLUSIONS

In customized lingual orthodontic treatment with miniscrew anchorage, compared with power arms located at the midpoint between the lateral incisors and canines, power arms located at the distal side of the canines will lead to larger initial lingual crown tipping, labial crown tipping, and occlusal crown extrusion of the maxillary anterior teeth in the sagittal and vertical planes, and a decreasing trend of the intercanine width in the transverse plane. Therefore, power arms located at the distal side of the canines are unfavorable for torque control and intercanine width control in customized lingual orthodontic treatment. Using power arms located at the midpoint between the lateral incisors and canines can get better anterior teeth torque control than using power arms located at the distal side of the canines, but still cannot achieve acceptable torque of maxillary anterior teeth without extra torque control methods, no matter whether its force application point is higher than, lower than, or equal to the level of the top of the miniscrews.

ACKNOWLEDGMENT

The authors express their gratitude to the Riton Biotechnology Co for providing the software which was essential for this study.

REFERENCES

1. Smith JR, Gorman JC, Kurz C, Dunn RM. Keys to success in lingual therapy. Part 1. J Clin Orthod 1986;20:252-61.
2. Fujita K. New orthodontic treatment with lingual bracket mushroom arch wire appliance. Am J Orthod 1979;6:657-75.
3. Wiechmann D. A new bracket system for lingual orthodontic treatment. Part 1: Theoretical background and development. J Orafac Orthop 2002;63:234-45.
4. Kojima Y, Kawamura J, Fukui H. Finite element analysis of the effect of force directions on tooth movement in extraction space closure with miniscrew sliding mechanics. Am J Orthod Dentofacial Orthop 2012;142:501-8.
5. Perillo L, Jamilian A, Shafieyoon A, Karimi H, Cozzani M. Finite element analysis of miniscrew placement in mandibular alveolar bone with varied angulations. Eur J Orthod 2015;37:56-9.
6. Jones ML, Hickman J, Middleton J, Knox J, Volp C. A validated finite element method study of orthodontic tooth movement in the human subject. J Orthod 2001;28:29-39.
7. Liang W, Rong Q, Lin J, Xu B. Torque control of the maxillary incisors in lingual and labial orthodontics: a 3-dimensional finite element analysis. Eur J Orthod 2009;135:316-22.
8. Lee SC, Park JH, Bayome M, Kim KB, Araujo EA, Kook YA. Effect of bone-borne rapid maxillary expanders with and without surgical assistance on the craniofacial structures using finite element analysis. Am J Orthod Dentofacial Orthop 2013;145:638-48.
9. Kim KY, Bayome M, Park JH, Kim KB, Mo SS, Kook YA. Displacement and stress distribution of the maxillofacial complex during maxillary protraction with buccal versus palatal plates: finite element analysis. Eur J Orthod 2015;37:275-83.
10. Gomez JP, Peña FM, Martínez V, Giraldo DC, Cardona CI. Initial force systems during bodily tooth movement with plastic aligners and composite attachments: A three-dimensional finite element analysis. Angle Orthod 2015;85:454-60.
11. Lee HK, Bayome M, Ahn CS, Kim SH, Kim KB, Mo SS, et al. Stress distribution and displacement by different bone-borne palatal expanders with micro-implants: a three-dimensional finite-element analysis. Eur J Orthod 2014;36:531-40.
12. Nihara J, Gielo-Perczak K, Cardinal L, Saito I, Nanda R, Uribe F. Finite element analysis of mandibular molar protraction mechanic using miniscrews. Eur J Orthod 2015;37:95-100.
13. Scuzzo G, Takemoto K. Biomechanics and comparative biomechanics. In: Scuzzo G, Takemoto K, editors. Invisible orthodontics. 1st ed. Berlin: Quintessenz Verlags; 2003. p. 55-60.
14. Scuzzo G, Takemoto K. Lingual orthodontics. 1st ed. Berlin: Quintessenz Verlags; 2010.

15. Lawson RB. Extraction treatment in lingual orthodontics. J Orthod 2013;40(Suppl 1):38-48.
16. Geron S. Anchorage considerations in lingual orthodontics. Semin Orthod 2006;12:167-77.
17. Hong RK, Heo JM, Ha YK. Lever-arm and mini-implant system for anterior torque control during retraction in lingual orthodontic treatment. Angle Orthod 2005;75:129-41.
18. Shan LH, Guo N, Zhou GJ, Qie H, Li CX, Lu L. Finite element analysis of bone stress for miniscrew implant proximal to root under occlusal force and implant loading. J Craniofac Surg 2015;26:2072-6.
19. LV Y, Zhang Z, Su Y, Yuan P, Ma W, Huang W, et al. Healing of root and surrounding periodontium after root damage with miniscrew implants: a histomorphologic study in dogs. Clin Oral Investig 2018;22:1103-11.
20. Poggio PM, Incorvati C, Velo S, Carano A. "Safe zones": a guide for miniscrew positioning in the maxillary and mandibulara arch. Angle Orthod 2006;76:191-7.
21. Kim JS, Seong-Hun K, Yoon-Ah K, Kyu-Rhim C, Nelsone G. Analysis of lingual en mass retraction and a palatal plate. Angle Orthod 2011;81:662-9.
22. Lombardo L, Scuzzo G, Arreghini A, Gorgun O, Ortan YO, Siciliani G. 3D FEM comparison of lingual and labial orthodontics in en masse retraction. Prog Orthod 2014;15:38.
23. Stamm T, Wiechmann D, Heinecken A, Ehmer U. Relation between second and third order problems in lingual orthodontic treatment. J Ling Orthod 2000;1:5-11.