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Stress and Movement Trends of Maxillary Anterior Teeth During Molar Distalization with Clear Aligners Under Different Arrangement Conditions: A Finite Element Study

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Abstract

Introduction:

The aim of this study is to investigate the force distribution of the anterior teeth with the different alignment statements during the molar distalization with clear aligners.

Methods

A three-dimensional (3D) finite element model of maxillary molar distalization with clear aligners (CA) and four types of anterior tooth arrangement was developed. These include Group A with properly aligned incisors, Group B with anterior teeth rotation alignment, Group C with labiolingual malpositioning of anterior teeth, and group D with anterior teeth absence. Each group simulated the sequential distal movement of the maxillary second molars by 0.2mm. The study recorded the trends of 3D displacement and force distribution in the maxillary incisors during the process of molar distalization

Results

the total displacement of the central incisors, lateral incisors, and canines in Group B was found to be the least. The total displacement of anterior tooth was similar in Groups A and D. Interestingly, the anterior teeth of all groups demonstrated an extrusion trend, and compared to Groups A and D, the Group B and Group C showed significantly less extrusion. Additionally, the lingual surface of the crowns in the anterior teeth area of Group B experienced higher compressive stress than in the other groups.

Conclusions

the arrangement of the anterior teeth affects the design of anchorage during the process of molar distalization. The crowded anterior teeth can significantly enhance the "anterior anchorage" during the molar distal movement, which potentially reduce the need for supplementary anchorage devices.

Background

Compared with the traditional appliance, clear aligners are favored due to their aesthetics, comfort, and precision [1]. As a push appliance, several studies have demonstrated that pushing the molars backward is one of the most predictable tooth movements with clear aligners [2–5]. Simon et al. reported that the efficiency of molar distalization with prescribed movement of at least 1.5mm was 88%[6].

The success of the molar distalization depend on many factors, especially, adequate anchorage[7–8]. Therefore, to achieve more effective and precise control during the molar push-back process, Class II elastic, micro-screw implants, and other auxiliary means are often employed to minimize the anterior

teeth labial inclination[9–15]. Many researches have focused on the the movement tendency and initial displacement of the posterior region during molar distalization, as well as the roles played by different attachments, elastic traction, or implant nails in this process [6, 19–24]. However, fewer reports are available on the alignment of anterior teeth and the force characteristics in the anterior teeth area during the molar push-back process.

Finite element analysis (FEA) is a digital simulation technique used to model and analyze the responses of teeth to orthodontic forces[16]. In the field of orthodontics, FEA has been extensively used to gain a deeper understanding of tooth movement and the application of forces. Several studies have employed FEA to analyze the biomechanical characteristics of maxillary molar distalization using clear aligners, such as comparisons of different attachments and traction devices [16–18]. In this study, we established a three-dimensional finite element model representing a commonly encountered and representative dental arrangement of the anterior teeth in clinical practice. This model was used to simulate the process of moving the molars distally with a clear aligner, and to explore the biomechanical characteristics of the anterior teeth under the influence of clear aligner.

Material and methods[16]

Materials and equipment

Cone beam computed tomography (CBCT) data (KaVo 3D eXamCBCT (USA), Sirona 3-in-1 CBCT (Germany)); MIMICS 21.0 software; GEOMAGIC Studio 2021; SOLIDWORK 2021; ANSYS Workbench 2024 (ANSYS, Pennsylvania, USA).

Relevant statement

The ethics committee of School of Stomatology, Lanzhou University, China, approved the study (LZUKQ-2023-033). The authors confirmed that all the methods were performed in accordance with the relevant guidelines and regulations.

Construction of the model

CBCT data (KaVo 3D eXamCBCT) were acquired class I with well-aligned dentition, no missing teeth, and healthy periodontal condition. First, the data were imported into MIMICS 21.0 software to generate three dimensional base models of the maxillary dentition. Then, we used GEOMAGIC Studio 2021 to optimize the basic model and create a surface model structure. The outer surface of the maxillary teeth roots was extended outwards by 0.25 mm to generate a preliminary model for PDL. The maxillary crown and attachment were extended outwards by 0.7 mm to simulate the thickness of the appliance, and each tooth was treated as an independent component. Finally, all components were imported into ANSYS Workbench 2024 to generate a three-dimensional finite element model for FEA. Furthermore, four groups

of models were created: (1) Group A: Group with anterior teeth alignment, (2) Group B: Group with anterior teeth rotation alignment (3) Group C: Group with anterior dental misalignment (4) Group D: Missing teeth 12 and 22 in the anterior region (Fig. 1)

"Bonded" contact was set between the roots and PDLs, as well as between the PDLs and alveolar bone. "Frictional" contact was set between the external surface of the clinical crown and the internal surface of the CA. The friction factor was set as 0.2 based on the reported literature. The upper surface of maxilla was "fixed", restricting all degrees of freedom for the elements. With these settings, convergence of the contact calculations for the model was achieved. [25]

Material properties

For simulation of the involved structures, We defined the physical properties for different structures. The alveolar bone, teeth, periodontal ligament (PDL), and clear aligners were assumed to exhibit linear elastic, isotropic, and homogeneous behaviors, with their mechanical parameters derived from previous studies. Differences between cortical bone and cancellous bone, as well as differences between enamel, dentin, and cementum, were not considered. Mechanical properties were inferred from previous studies[18, 24] (Table 1).

Table 1
Material properties

Components	Young's Modulus(Mpa)	Poisson's Ratio
Alveolar bone	1370	0.30
Teeth	19, 600	0.30
PDL	0.69	0.45
CA	1, 000	0.4

Design of a 3D coordinate system

A 3D coordinate system was used to define the direction of x, y and z axes in order to clearly determine the displacement value of the anterior teeth. The X-axis represented the direction of the coronal plane with the positive mesial direction ; the Y-axis represents the sagittal plane with the positive lingual direction, and the Z-axis represents the vertical plane with the positive gingival direction .

Loading method

In the 3D model, the added forces in clinical usage were imitated, the second molar was first moved back 0.20mm into the sagittal direction and the forces resulted in deformation of the aligner. The forces of the aligner deformation on each anterior tooth were then calculated (ANSYS Workbench 2024) [20].

Results

Movement Trends in the Anterior Teeth (Figs. 2, 3 and 5)

In the mesiodistal dimension, the buccolingually malpositioned group (Group C) exhibited a pronounced distal movement trend. The well-aligned group (Group A) and the rotated group (Group B) demonstrated similar mesiodistal movement patterns, with most incisors in Group B showing the smallest initial displacement.

In the labiolingual dimension, all anterior teeth across groups displayed a trend of crown movement toward the labial side, except for tooth 22 in Group C. In cases with no missing anterior teeth, most teeth in the rotated group (Group B) exhibited the smallest initial displacement.

In the vertical dimension, all incisors showed an extrusion trend except for tooth 22 in Group C. The rotated group (Group B) presented the least amount of extrusion, with some teeth even exhibiting intrusive movement.

Overall, during clear aligner-mediated molar distalization, the anterior teeth consistently demonstrated a labial crown tipping trend. The rotated group (Group B) showed the smallest initial displacement across all three dimensions: mesiodistal, labiolingual, and vertical.(Fig. 5)

Periodontal Ligament Stress Distribution

Stress was primarily concentrated near the gingival margin and on the buccolingual surfaces, while stress values on the mesiodistal surfaces were relatively low. When no anterior teeth were missing, the rotated/crowded anterior tooth group exhibited the lowest equivalent stress values in the periodontal ligament, indicating the least stress. In scenarios with a missing anterior tooth, no significant change in equivalent stress was observed in the periodontal ligament of the maxillary central incisor. (Fig. 4)

Figure 5. Displacement tendencies of crowns and roots in maxillary anterior teeth across different groups

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Discussion

The distalization of maxillary molars is commonly used to treat mild and moderate skeletal Class II cases, aiming to achieve the correction from a molars Class II to a molars Class I through a non-extraction orthodontic treatment plan. [10]

Simon et al. [6] found that when designed for an average distal movement of 2.7 mm, the efficiency of maxillary molar distalization was the highest (reached to 88%). The authors reported that accuracy was best when there were attachments on the teeth to assist in movement. They also emphasized the crucial

role of staging in treatment predictability. However, their study focused on the movement efficiency of molars and did not consider the arrangement of anchorage teeth, especially the arrangement of anterior teeth.

clear aligners use elastic resin as the force carrier and apply continuous, low-intensity orthodontic forces through conformal deformation with the tooth surface, and their force transmission efficiency is highly dependent on the consistency of tooth alignment within the dental arch. During the distalization of maxillary molars with clear aligners, based on the core principle of "action and reaction" in orthodontic biomechanics, when the aligner exerts a distal driving force on the molars through elastic deformation, an equal and opposite reactive force is inevitably generated. This reactive force is transmitted through the entire dental arch to the anterior teeth and non-target teeth in the posterior region that serve as anchorage units, forming a dynamic balance between the anchorage system and the orthodontic force [26]. The stability of the anchorage system directly determines the actual efficiency and displacement accuracy of molar distalization, while the initial alignment status of anchorage teeth, as a key anatomical variable affecting anchorage strength, requires a comprehensive analysis of its clinical value in combination with the mechanical characteristics of different orthodontic techniques.

This study employed three-dimensional finite element analysis to simulate different anterior tooth alignment patterns during clear aligner-mediated molar distalization. As shown in Fig. 4, each group exhibited distinct movement characteristics in both labiolingual and vertical dimensions. The rotated anterior teeth group (Group B) demonstrated the smallest initial displacement for each incisor compared to other groups, indicating the strongest anterior anchorage during molar distalization. Both the labiolingually malpositioned group (Group C) and well-aligned group (Group A) showed significant labial inclination of tooth 12 with substantially greater initial displacement than Group B, suggesting that labiolingual malpositioning fails to enhance and may even deplete anterior anchorage .

During clear aligner-mediated molar distalization, reactive forces typically induce undesirable labial inclination of anterior teeth. Stronger anterior anchorage results in greater distal movement trend of second molars, which suggested that increasing anchorage can improve the efficiency of molar distalization. As illustrated in Fig. 1, Group B (rotated anterior teeth) exhibited the greatest initial distal displacement of second molars, while the missing anterior teeth group showed significantly less movement trend than that of the other groups. These findings further confirm that rotated anterior tooth alignment enhances anterior anchorage effectiveness.

In the vertical dimension, most anterior teeth exhibited extrusion, consistent with clinical observations of anchorage loss. The rotated group (Group B) showed minimal vertical displacement, with some teeth even intruding, suggesting that initial rotation or crowding may enhance vertical anchorage under effective aligner control, which is clinically relevant for overbite management.

In the mesiodistal dimension, the buccolingually malpositioned group (Group C) demonstrated pronounced distal movement, while the well-aligned (Group A) and rotated (Group B) groups displayed similar but smaller displacements. This likely results from the deviation of Group C teeth from the

normal arch curvature, leading to a greater distal force component. Clinically, additional anchorage measures, such as optimized attachments or micro-implants, should be considered for severely malpositioned anterior teeth during molar distalization to prevent unwanted movement.

Regarding canines, their displacement did not show significant group-specific trends in this study, likely due to their unique anatomical and biomechanical characteristics.

Notably, the atypical displacement of tooth 22 in Group C—such as lack of extrusion and atypical labiolingual movement—appears related to its smaller crown size and the absence of additional attachments in this experimental setup. This highlights the need for enhanced aligner retention, possibly through optimized attachments, when moving teeth with smaller clinical crowns to ensure predictable control.

Considering that orthodontic treatment primarily relies on tooth movement, more anchorage control is required. [27] In clinical, we need to consider the anchorage issue thoroughly to achieve a higher efficiency of molar distal movement. Our research suggests that when the anterior teeth are crowded due to twisting, it may not be necessary to use additional appliance such as mini-implant to reinforce the anchorage during the process of pushing molars back, as the anterior region already has strong anchorage[28].

To minimize experimental variables, this study did not incorporate attachments and consider the occlusal contacts between maxillary and mandibular dentitions. However, in clinical practice, attachments are commonly used to enhance appliance control for better management of posterior tooth movement and anterior torque. Occlusal contacts may significantly alter the anterior tooth loading pattern, thereby affecting anchorage efficacy. Future studies incorporating attachments in both posterior and anterior regions could provide more clinically relevant simulations of anterior tooth effects during clear aligner-mediated molar distalization.

This study specifically demonstrates that rotated anterior teeth configuration enhances "anterior anchorage." The potential differential effects of various rotation angles warrant further investigation. Subsequent studies should simulate additional clinical scenarios to enhance the generalizability of conclusions. Besides, Randomized clinical trials would be valuable to further validate these findings.

Conclusions

1. Compared to well-aligned anterior teeth, anterior teeth with labiolingual malpositioning, and missing anterior teeth, rotated anterior teeth demonstrated the least labial inclination tendency and initial displacement during molar distalization, along with a significantly reduced extrusion tendency.

2. During clear aligner-mediated molar distalization, rotated anterior teeth effectively enhance "anterior anchorage" potential.

Declarations

Ethics approval and consent to participate

This study was approved by the Institutional Review Board of the School of Stomatology, Lanzhou University (approval number: LZUKQ-2024-62). The finite element model was constructed based on computed tomography (CT) data obtained from a healthy volunteer, who provided written informed consent prior to participation.

Consent for publication

The volunteer whose CT data were used in this study has provided written informed consent for the publication of this study and any accompanying anonymized images. No individual person's data are presented in this manuscript.

Availability of data and material

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Not applicable

References

1. Weir T. Clear aligners in orthodontic treatment. Aust Dent J 2017; 62:58–62.
2. Wu D, Zhao Y, Ma M, Zhang Q, Lei H, Wang Y, Li Y, Chen X. Efficacy of mandibular molar distalization by clear aligner treatment. Zhong Nan Da Xue Xue Bao Yi Xue Ban. 2021 Oct 28;46(10):1114-1121. doi: 10.11817/j.issn.1672-7347.2021.200391.
3. Inchingolo A.M, Inchingolo A.D, Carpentiere V, Del Vecchio G, Ferrante L, Di Noia A, Palermo A, Di Venere D, Dipalma G, Inchingolo F. Predictability of Dental Distalization with Clear Aligners:A Systematic Review. Bioengineering.2023; 10: 1390.doi: 10.3390/bioengineering10121390
4. Galan-Lopez L., Barcia-Gonzalez J., Plasencia E. A systematic review of the accuracy and efficiency of dental movements with Invisalign(R) Korean J. Orthod. 2019; 49:140–149. doi: 10.4041/kjod.2019.49.3.140.
5. Aikaterini, Papadimitriou, Sophia,et al.Clinical effectiveness of Invisalign orthodontic treatment: a systematic review.[J].Progress in orthodontics, 2018.DOI:10.1186/s40510-018-0235-z.
6. Simon M, Keilig L, Schwarze J, Jung BA, Bourauel C. Treatment outcome and efficacy of an aligner technique—regarding incisor torque, premolar derotation and molar distalization. BMC Oral Health. 2014; 14: 68. doi: 10.1186/1472-6831-14-68.

7. Mao B, Tian Y, Liu D, Zhou Y, Wang S. The effect of maxillary premolar distalization with different designed clear aligners: a 4D finite element study with staging simulation. Prog Orthod. 2024 Dec 2;25(1):46. doi: 10.1186/s40510-024-00545-z.
8. Miao Z, Yang Y, Zhang H, Zheng C, Gao X, Zhu J, Han Y, Wang S. Anchorage loss in maxillary premolar and anterior teeth during maxillary molar distalization in clear aligner treatment. Am J Orthod Dentofacial Orthop. 2025 Jun;167(6):690-702. doi: 10.1016/j.ajodo.2025.01.010.
9. Wang Q, Dai D, Wang J, Chen Y, Zhang C. Biomechanical analysis of effective mandibular enmasse retraction using Class II elastics with a clear aligner: a finite element study. Prog Orthod. 2022 Jul 11;23(1):23. doi: 10.1186/s40510-022-00417-4.
10. Cheng Y, Liu X, Chen X, Li X, Fang S, Wang W, Ma Y, Jin Z. The three-dimensional displacement tendency of teeth depending on incisor torque compensation with clear aligners of different thicknesses in cases of extraction: a finite element study. BMC Oral Health. 2022 Nov 16;22(1):499. doi: 10.1186/s12903-022-02521-7.
11. Padmanabhan A, Khan Y, Lambate V, K U, Naveed N, Singh M, Nagi PK. Efficacy of Clear Aligners in Treating Class III Malocclusion with Mandibular Molar Distalization: A Systematic Review. Cureus. 2023 Nov 1;15(11): e48134. doi: 10.7759/cureus.48134.
12. Cui J, Yao C, Zhang Z, et al. Maxillary molar distalization treated with clear aligners combined with mini-implants and angel button using different traction force: a finite element study. Comput Methods Biomech Biomed Engin. 2023;1–10. doi: 10.1080/10255842.2023.2183735.
13. Gao H, Luo L, Liu J. Three-dimensional finite element analysis of maxillary molar distalization treated with clear aligners combined with different traction methods. Prog Orthod. 2024 Dec 9;25(1):47. doi: 10.1186/s40510-024-00546-y.
14. Guo R, Lam XY, Zhang L, Li W, Lin Y. Biomechanical analysis of miniscrew-assisted molar distalization with clear aligners: a three-dimensional finite element study. Eur J Orthod. 2024 Jan 1;46(1): cjad077. doi: 10.1093/ejo/cjad077.
15. Tang Z, Long H, Liu L, Lai W, Jian F. Influence of attachment position and torque overcorrection on arch expansion in clear aligner treatment: a three-dimensional finite element analysis. Angle Orthod. 2025 Mar 20. doi: 10.2319/061424-466.1.
16. Ji L, Li B, Wu X. Evaluation of biomechanics using different traction devices in distalization of maxillary molar with clear aligners: a finite element study. Comput Methods Biomech Biomed Engin 2023; 26:559–67. doi: 10.1080/10255842.2022.2073789.
17. Ayidaga C, Kamiloglu B. Effects of variable composite attachment shapes in controlling upper molar distalization with aligners: a nonlinear finite element study. J Healthc Eng 2021; 2021:5557483. doi: 10.1155/2021/5557483.
18. Liu X, Cheng Y, Qin Wet al. Effects of upper-molar distalization using clear aligners in combination with Class II elastics: a three-dimensional finite element analysis. BMC Oral Health 2022; 22:546. doi: 10.1186/s12903-022-02526-2.

19. Kang F, Wu Y, Cui Y, Yuan J, Hu Z, Zhu X. The displacement of teeth and stress distribution on periodontal ligament under different upper incisors proclination with clear aligner in cases of extraction: a finite element study. Prog Orthod. 2023 Nov 20;24(1):38. doi: 10.1186/s40510-023-00491-2.
20. Gao J, Guo D, Zhang X, Cheng Y, Zhang H, Xu Y, Jin Z, Ma Y. Biomechanical effects of different staging and attachment designs in maxillary molar distalization with clear aligner: a finite element study. Prog Orthod. 2023 Dec 4;24(1):43. doi: 10.1186/s40510-023-00493-0.
21. D'Anto V, Valletta R, Ferretti R, et al. Predictability of Maxillary Molar Distalization and Derotation with Clear Aligners: A Prospective Study. Int J Environ Res Public Health. 2023;20. doi: 10.3390/ijerph20042941.
22. Kuguoglu A, Akarsu-Guven B. Evaluation of the effects of the third molar on distalization and the effects of attachments on distalization and expansion with clear aligners: Three-dimensional finite element study. Korean J Orthod. 2025 Jan 25;55(1):69-81. doi: 10.4041/kjod24.202.
23. Zarif Najafi H, Pakshir HR, Bahraini F. Stress Distribution and Tooth Displacement Analysis of Maxillary Molar Distalization by Different Designs of Jig in a Finite Element Study. J Dent (Shiraz). 2025 Mar 1;26(1):33-47. doi: 10.30476/dentjods.2024.100556.2230.
24. GOMEZ J P, PEÑA F M, MARTÍNEZ V, et al. Initial force systems during bodily tooth movement with plastic aligners and composite attachments: A three-dimensional finite element analysis[J]. Angle Orthod, 2015, 85(3): 454-460. doi: 10.2319/050714-330.1.
25. Hmud R, Alamri A. Evaluating the efficacy and predictability of distalization protocols for maxillary molars in Class II treatment with clear Aligners: A narrative review. Saudi Dent J. 2024 Sep;36(9):1184-1189. doi: 10.1016/j.sdentj.2024.06.019.
26. Proffit WR, Fields HW Jr, Sarver DM. Contemporary Orthodontics. 6th ed. St. Louis: Elsevier Saunders; 2013: 452-478.
27. Bowman SJ, Celenza F, Sparaga J, Papadopoulos MA, Ojima K, Lin JC. Creative adjuncts for clear aligners, part 1: class II treatment. J Clin Orthod. 2015;49:83–94. PMID: 26106819.
28. Liu H, Tang Z, Gong Z, Ye C, Wu H. Evaluation of maxillary miniscrew-anchored molar distalization appliance versus clear aligners in adult with Class II malocclusion: study protocol for a randomized controlled trial. Trials. 2025 Apr 7;26(1):123. doi: 10.1186/s13063-025-08827-5.

Figures

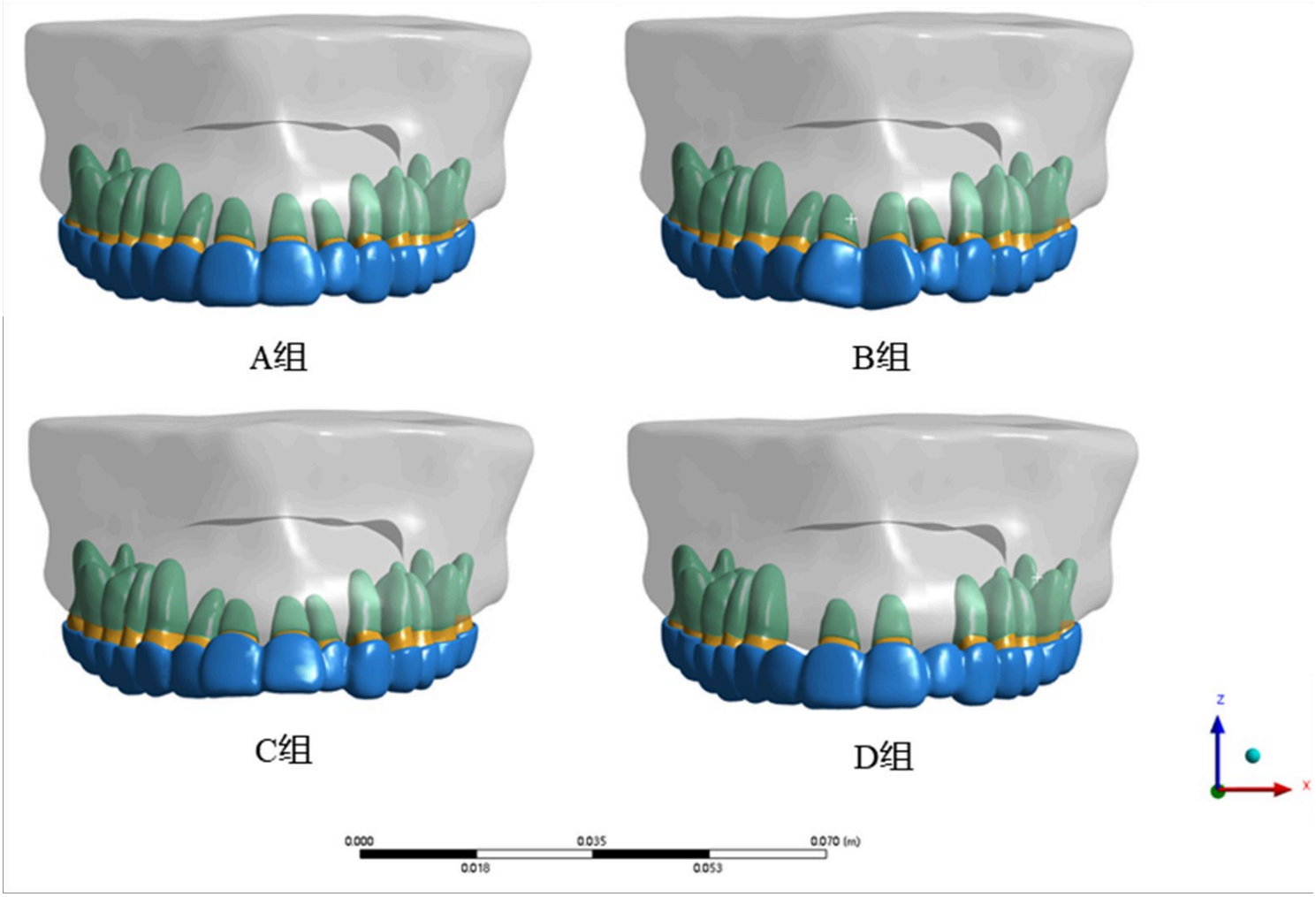


Figure 1

Finite element models for different groups.

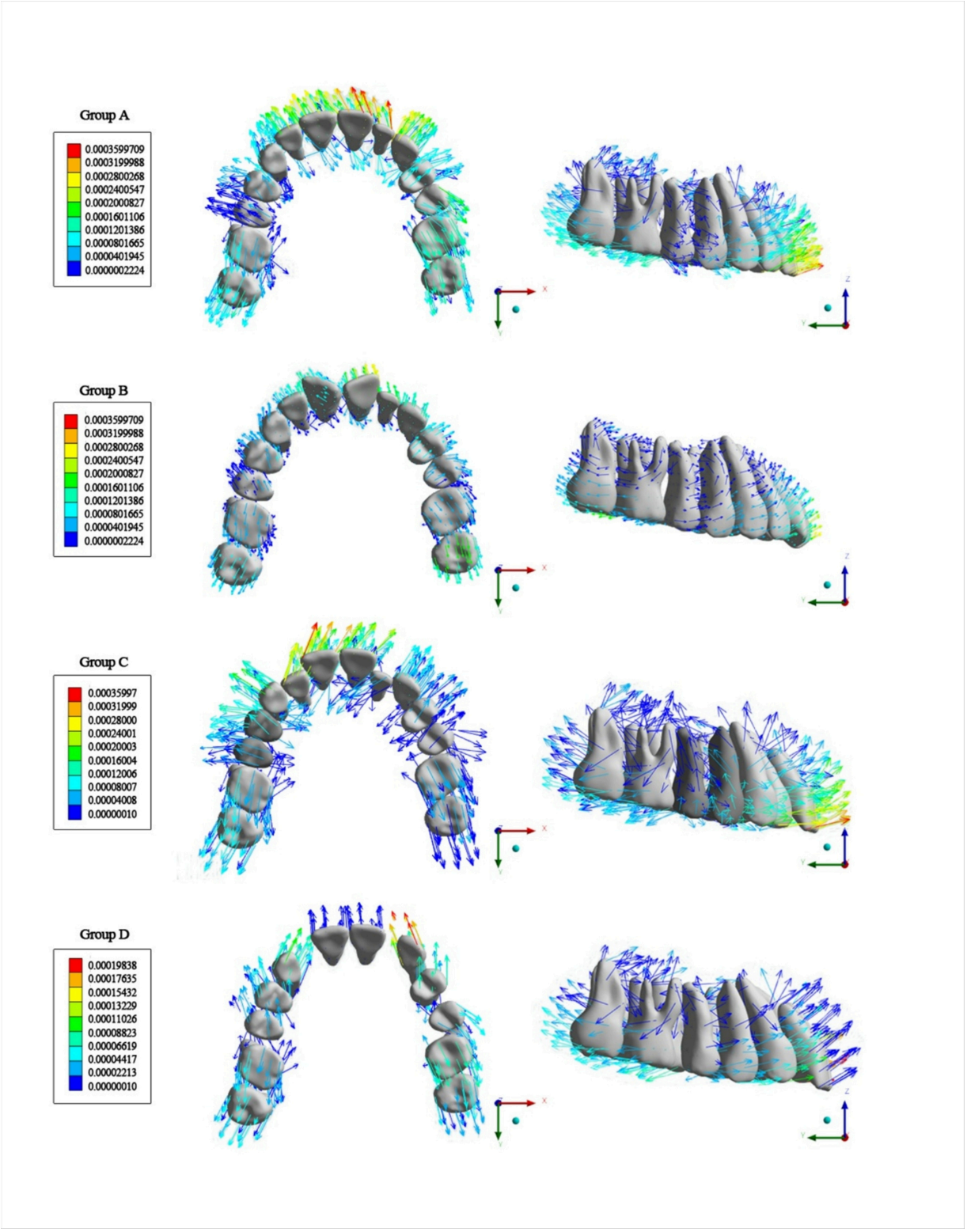


Figure 2

Initial displacement tendencies distribution in the maxillary dentition with clear aligners, showing the teeth13-23 in sagittal and axial views.

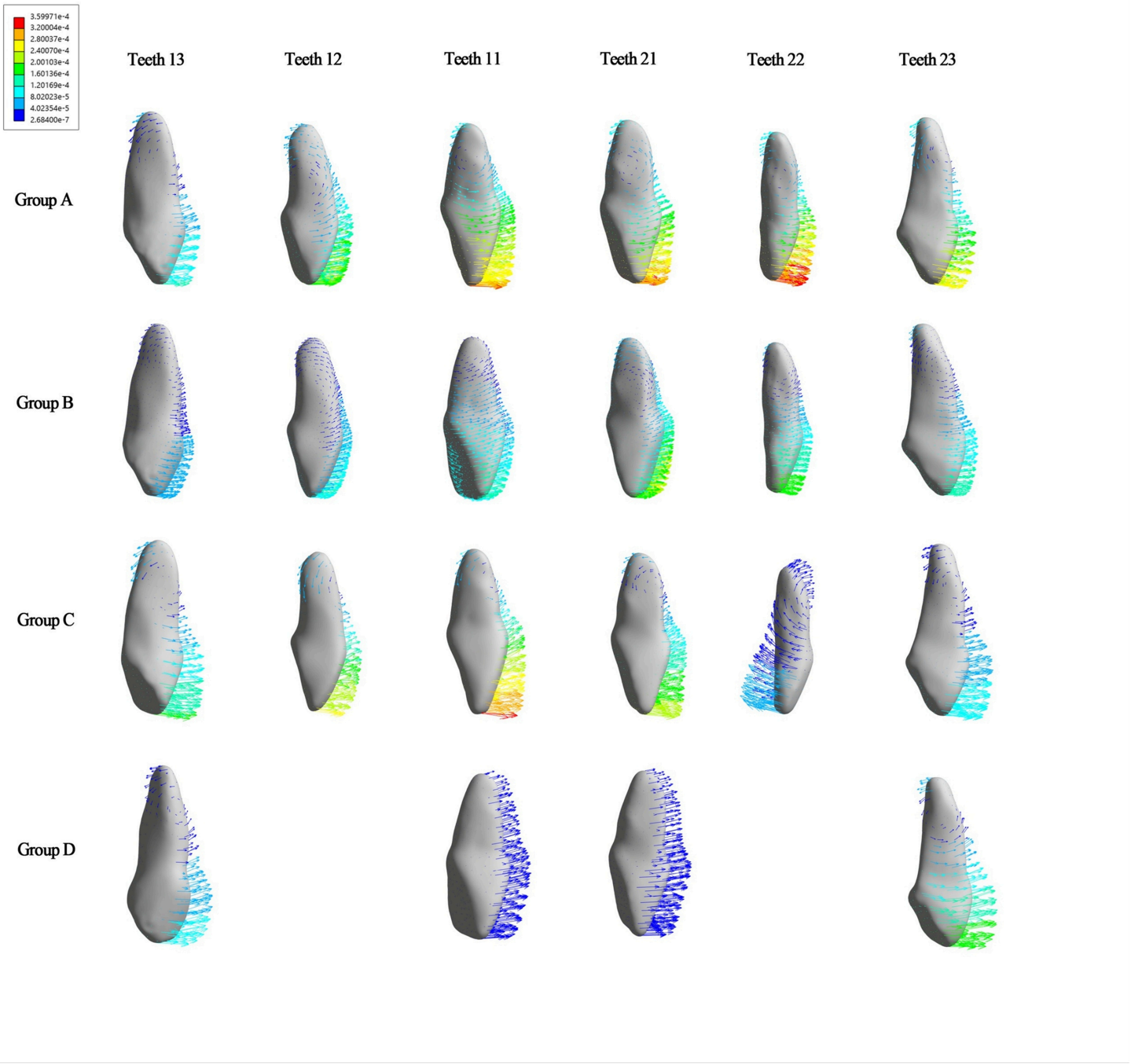


Figure 3

The displacement tendencies of the anterior from different groups.

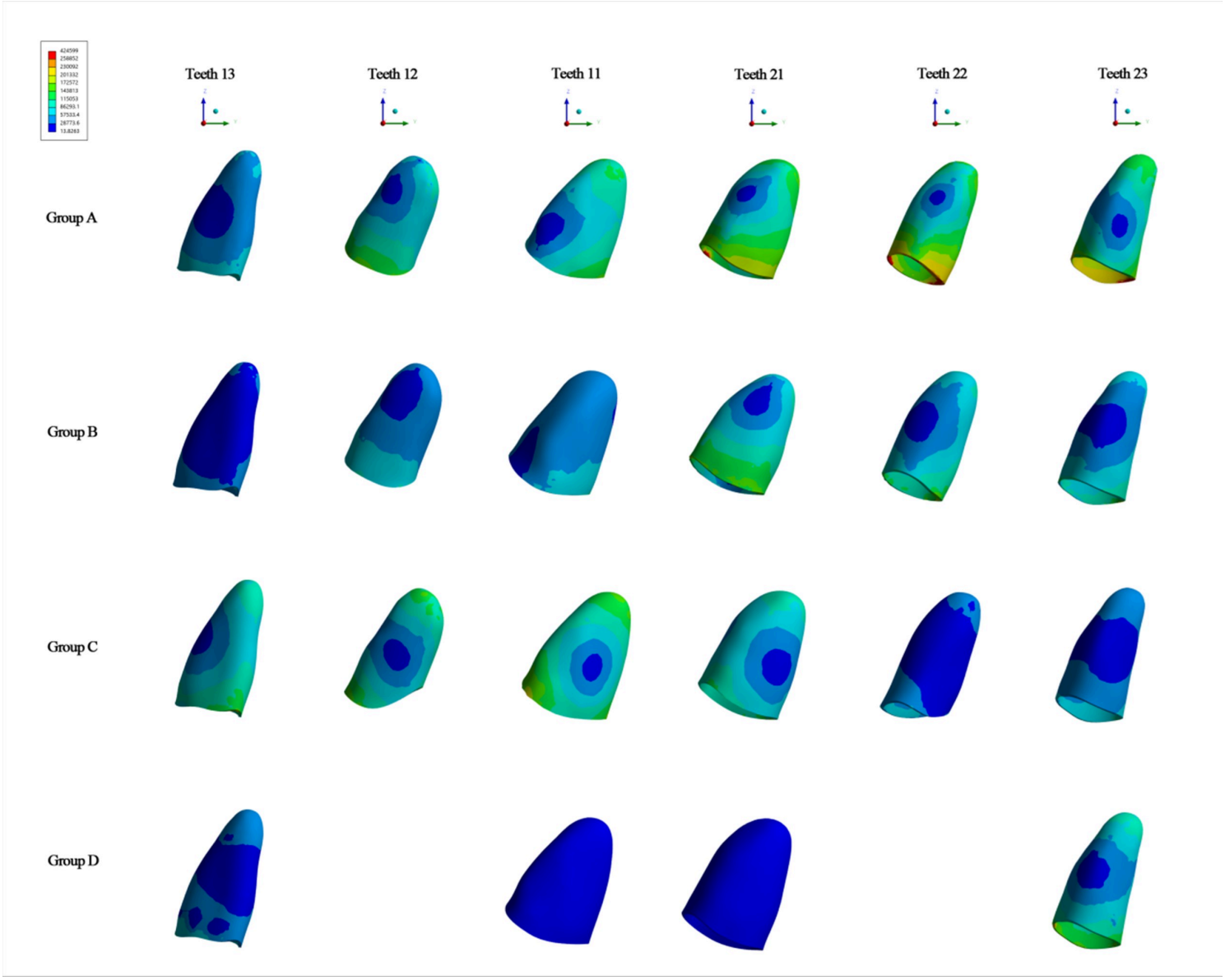


Figure 4

Equivalent Stress distribution in the maxillary Periodontal ligament with clear aligners

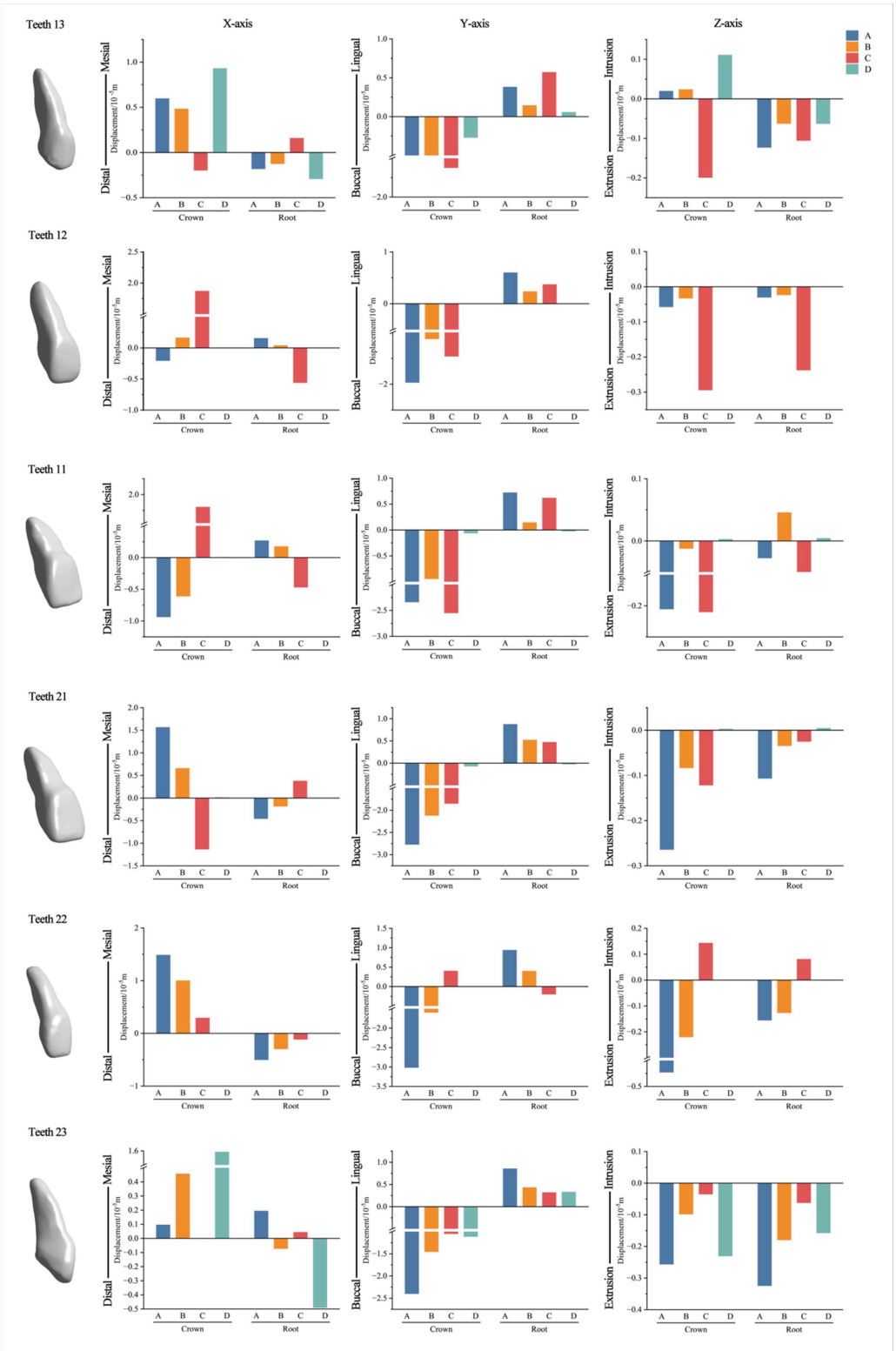


Figure 5

Displacement tendencies of crowns and roots in maxillary anterior teeth across different groups