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The effects of clinical crown length on the sagittal movement of maxillary central incisor in clear aligner treatment: a finite element exploration

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Abstract

Background The mechanism of force application in clear aligner treatment involves wrapping the clinical crowns, suggesting that the size of the clinical crowns may impact tooth movement. The present finite element study aimed to explore the impact of clinical crown length on the sagittal movement of maxillary central incisor in clear aligner treatment.

Methods The standard maxillary dentition model was developed using computer tomography scanning. Finite element models of the maxillary dentition, alveolar bone, periodontal ligament, and aligners were established. Twelve model groups were divided based on different clinical crown lengths and attachments' position to simulated the tipping and translational movements of the right maxillary central incisor. The dimensions of the short and long clinical crowns were determined based on epidemiological evidence, and appropriate models were constructed by shortening or elongating the normal incisors by 20% along the longitudinal axis of the tooth. Horizontal rectangular attachments were constructed at the clinical crown center of the short, normal and long clinical crowns. These attachments were categorized into four types: no attachment, labial attachment, palatal attachment and labio-palatal attachments. The finite element analysis focused on evaluating the contact pressure distribution on the crown, displacements, rotations, and von Mises stress in PDL of the right maxillary central incisors.

Results In tipping movement, the long clinical crown exhibited the highest crown displacement and rotation, enhancing the efficiency. In translational movement, the long clinical crown had the lowest TL/CD value, losing less torque during the crown displacement. However, the short clinical crown had the lowest M_x/F_y value, with a greater tendency to move bodily rather than long ones. The von Mises stress distribution in PDL was similar between the two

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types of movement, while the maximum von Mises stress increased with increasing clinical crown lengths in tipping movement. Labio-lingual attachment had the optimal effect in tipping and translational movement.

Conclusions Clinical crown length has considerable influences on the efficiency, movement behavior, and maximum von Mises stress of the PDL in the sagittal movement of maxillary center incisor in clear aligner treatment. Moreover, attachments also influence the movement efficiency of the incisor.

Keywords Clinical crown length, Maxillary central incisor, Clear aligner treatment, Tooth movement, Finite element analysis

Introduction

Clinical crown length (CCL) is a critical factor to orthodontic treatment due to its multifaceted impact on tooth movement biomechanics, treatment efficacy, aesthetics, and long-term stability. For example, longer crowns may alter leverage, affecting extrusion/intrusion mechanics, whereas shorter crowns might require modified force systems to achieve desired movements. Torque and rotational control depend on crown length, with longer crowns may require altered force vectors to account for shifted centers of resistance. To anchorage control, sometimes teeth with insufficient clinical crown length may fail as stable anchors, risking unintended movement. Specifically in fixed appliance treatment, proper bracket positioning relies on clinical crown length, and moreover, short crowns may challenge bracket adhesion, increasing failure rates.

After more than two decades of rapid development, clear aligner treatment has achieved satisfactory clinical results [1, 2]. Clear aligners exert orthodontic force via the deformation caused by a pre-designed mismatch with tooth crowns. Therefore, according to clinical observations and experience, the clinical crown length affects the area of the tooth surface wrapped by the aligners which seem to have a relationship with the treatment efficacy, with shorter clinical crown length is not benefical to better outcomes of clear aligner treatment. However, to our best knowledge, the investigation into this problem is currently lacking. There exist few clinical or basic research works looking into the effect of crown dimensions on clear aligner treatment, particularly the clinical crown length [3, 4]. Therefore, it is of great significance to realize the impact of clinical crown length on clear aligner treatment.

Understanding the influence of clinical crown length on orthodontic tooth movement in clear aligner therapy is critical for several reasons: First, biomechanical efficiency. The clinical crown length affects the force application and distribution during orthodontic treatment. Clear aligners apply forces to the crowns of the teeth, and variations in crown length can influence how these forces are transmitted to the roots and surrounding periodontal structures. Proper force application is essential for efficient and predictable tooth movement. Second, anchorage control. Teeth with shorter clinical crowns may offer less anchorage because there is less surface area for the aligner to grip. This can affect the overall treatment plan, especially in cases requiring significant tooth movement or space closure. Third, periodontal health. Excessive or improperly directed forces can increase the risk of root resorption. Proper consideration of clinical crown length helps in maintaining periodontal health by ensuring that forces are not excessive or detrimental to the supporting structures. Understanding how clinical crown length influences force distribution helps in minimizing this risk by ensuring that forces are applied in a controlled and biologically safe manner.

Clear aligners could have limitations in some kinds of tooth movement, including the labiolingual movement of anterior teeth [5, 6]. On the other hand, maintaining the torque of anterior teeth is critical to their sagittal movement, especially in extraction cases; however, torque loss may occur during clear aligner treatment due to the limited rigidity of material [7, 8]. Due to the incomplete understanding of the force transmission mechanism of the clear aligner, predicting the outcomes of the clear aligner therapy remains challenging.

Finite element analysis (FEA), as a powerful numerical approach commonly exploited for mechanical analysis of complex objects, is now a crucial approach in orthodontic research and is broadly employed in various explorations owing to its effective, accurate, and non-invasive features. Currently, the main application of finite element analysis in orthodontics is to realize the initial displacement and stress distribution in teeth and other tissues instantly after force loading [9–11].

The purpose of our study was to establish the finite element models of the maxillary central incisors with various clinical crown lengths and investigate the effects of clinical crown length on their movement behavior, displacement pattern and stress distribution in sagittal movement, including palatal tipping and translational, with clear aligner treatment.

Materials and methods

This in vitro study using finite element analysis, a phenomenological approach, to evaluate the biomechanical effects of different clinical crown lengths on the sagittal

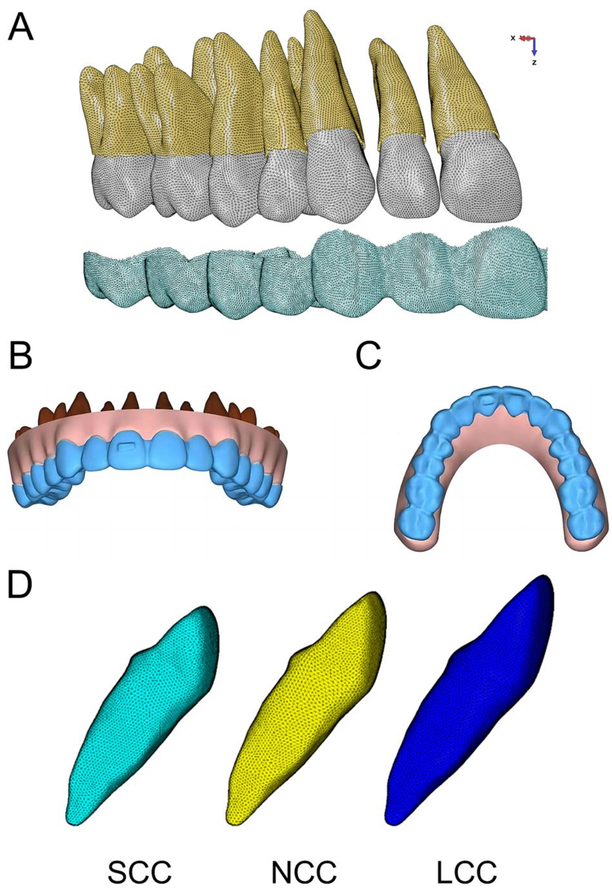

Fig. 1 Finite element models are established. (**A**) Standard right maxillary dentition, including PDL and clear aligner. (**B**) Maxillary dentition and clear aligner with labial horizontal rectangular attachment. (**C**) Maxillary dentition and clear aligner with palatal horizontal rectangular attachment. (**D**) Right maxillary central incisors with different clinical crown lengths

movement of maxillary central incisor with clear aligner treatment. The standard maxillary dentition model was developed using computer tomography scanning. The finite element models of the maxillary dentition, alveolar bone, periodontal ligament, and aligners were then established. Twelve model groups were divided based on the different clinical crown lengths and attachments' position to simulated the tipping and translational movements of the right maxillary central incisor. Two types of tooth movement, tipping and translational movements, were applied on the incisor. The finite element analysis in this study centered on evaluating the contact pressure distribution on the crown, displacements, rotations, and von Mises stress in PDL of the right maxillary central incisors. These parameters were analyzed using finite element software to understand the biomechanical behavior of the tooth and surrounding tissues under various loading conditions.

Table 1 Mechanical properties adopted in the finite element analysis

Material	Young's modulus (MPa)	Poisson's ratio
Periodontal ligament	0.068	0.49
Clear aligner	2000	0.4
Tooth	Rigid	
Alveolar bone	Rigid	
Attachment	12,500	0.36

Model establishment

A three-dimensional (3D) model of standard maxillary dentition was developed by computer tomography (CT) scanning in a dental study model (PE-ANA009; Nissin Dental Products, Kyoto, Japan). Periodontal ligaments (PDLs) were constructed around the roots with an average thickness of 0.25 mm by employing Geomagic Design X (3D Systems, South Carolina, USA). The clear aligner models were constructed by 0.50 mm outwards from crowns, and the thickness of the aligner was considered to be uniform. The horizontal rectangular attachments were constructed labially and/or lingually on clinical crown center of the right maxillary central incisor with dimensions of 3 mm x 2 mm x 1 mm (length x width x thickness) by employing Geomagic Design X, as presented in Fig. 1B and C.

Material properties and meshing

The meshing of models was conducted using HyperMesh 13.0 (Altair Engineering, Michigan, USA), as presented in Fig. 1A. As described in the literature, Young's moduli of teeth and alveolar are much higher than those of the PDL and aligners [12]. Under the given circumstances, teeth and alveolar bone were defined as rigid bodies and meshed using rigid triangular shell elements to facilitate the analysis. The PDL was assumed as linear elastic materials and meshed via pentahedron elements. The inner layer of the PDL shared nodes with teeth, while the outer layer shared nodes with alveolar bone. Aligners were set as isotropic, homogeneous, and elastoplastic materials and meshed by implementing triangular shell elements. The properties of materials are listed in Table 1. The interface between aligners and teeth was defined as surface-to-surface contacts with a friction coefficient of 0.3. The fixed constraints were applied to elements of the alveolar bone.

Model grouping

To establish appropriate models for exploring the impacts of clinical crown length of maxillary central incisor, previous tooth morphological investigations on anterior teeth were reviewed Table 2. Based on previous findings, the clinical crown length of the maxillary central incisor follows a normal distribution [13, 14], and the means of that are mostly in the range of 9.8–10.2 mm,

Table 2 Clinical crown length of maxillary central incisors of healthy individuals from different studies

Study	Mean of clinical crown length (mm)	SD of clinical crown length (mm)	Gender	Race/people	Age (years)	Sample size
Sterrett et al., 1999 [16]	10.19	0.94	Male	Caucasian	≥ 20	24
	9.39	0.86	Female	Caucasian	≥ 20	47
Konikoff et al., 2007 [17]	10.1 (right)	1.3	Non-specific	Non-specific	17–23	31
	9.8 (left)	1.2	Non-specific	Non-specific	17–23	31
Condon et al., 2011 [13]	10.37	1.24	Male	Irish	18–25	40
	9.93	0.97	Female	Irish	18–25	69
Zhao et al., 2015 [18]	10.26	0.99	Non-specific	Chinese	18.34 (mean)	101
Orozco-Varo et al., 2015 [19]	10.23 (right)	0.79	Non-specific	European	33.94 (mean)	412
	10.22 (left)	0.78	Non-specific	European	33.94 (mean)	412
Hossain et al., 2016 [20]	9.98	1.05	Male	Malaysians	20–26	55
	9.45	1.15	Female	Malaysians	20–26	146
Song et al., 2017 [21]	9.94	0.95	Non-specific	Korean	24–32	50
Palone et al., 2020 [22]	10.1	1.0	Non-specific	Italian	29.6 (mean)	40
	9.6	0.9	Non-specific	Mozambican	23.4 (mean)	29

while the standard deviations (SD) are approximately around 1.0 mm. Then we considered the reference values of mean and SD equal to 10.0 mm and 1.0 mm for subsequent calculations. The calculations of the upper reference limit (URL) and the lower reference limit (LRL) of a 95% reference interval of a normally distributed population [15]:

$$\mathrm{URL} = \mathrm{Mean} + 1.96 \times \mathrm{SD}$$

$$\mathrm{LRL} = \mathrm{Mean} - 1.96 \times \mathrm{SD}$$

The lengths of the short clinical crown (SCC), the normal clinical crown (NCC), and the long clinical crown (LCC) of maxillary central incisors are determined as followed (1.96 is rounded up to 2.0):

$$\mathrm{SCC} = 10.0 - 2 \times 1.0 = 8.0\,\mathrm{mm}$$

$$\mathrm{NCC} = 10.0\,\mathrm{mm}$$

$$\mathrm{LCC} = 10.0 + 2 \times 1.0 = 12.0\,\mathrm{mm}$$

Since both values of the SCC and LCC presented a 20% discrepancy with the value of the NCC, we elongated or shortened the original model of the right maxillary central incisor along the longitudinal axis of the tooth by 20% and proceeded in constructing the models with long clinical crown length or short clinical crown length (Fig. 1D). The developed models for the SCC, NCC, and LCC groups were assembled with the standard maxillary dentition and corresponding aligners to generate complete models for finite element analysis, with a total of 312,056, 324,358, and 328,547 elements, respectively.

The models were divided into four groups depending on the attachment location on the maxillary central incisor: No attachment (NA), Labial attachment (LA), Palatal attachment (PA), Labio-palatal attachments (LPA).

To conclude, the dimensions of the short and long clinical crowns of the right maxillary central incisor were determined based on epidemiological evidence, and appropriate models were constructed by shortening or elongating the normal incisors by 20% along the longitudinal axis of the tooth. Horizontal rectangular attachments were constructed at the clinical crown center of the short, normal and long clinical crown of the right maxillary central incisor. These attachments were categorized based on their position into four types: NA, LA, PA and LPA.

Twelve model groups were divided based on the clinical crown lengths and attachments' position.

Group1: SCC-NA(short clinical crown no attachment).
Group2: SCC-LA(short clinical crown labial attachment).
Group3: SCC-PA(short clinical crown palatal attachment).
Group4: SCC-LPA(short clinical crown labio-palatal attachments).
Group5: NCC-NA(normal clinical crown no attachment).
Group6: NCC-LA(normal clinical crown labial attachment).
Group7: NCC-PA(normal clinical crown palatal attachment).
Group8: NCC-LPA(normal clinical crown labio-palatal attachments).
Group9: LCC-NA(long clinical crown no attachment).
Group10: LCC-LA(long clinical crown labial attachment).

Group11: LCC-PA(long clinical crown palatal attachment).
Group12: LCC-LPA(long clinical crown labio-palatal attachments).

Loading conditions

In the current study, two types of tooth movement, tipping and translational movements, were applied on the right maxillary central incisor. In tipping movement, the incisor was supposed to experience a 0.30 mm palatal displacement of the incisal edge without the root apex displacement (Fig. 2A). In translational movement, a palatal bodily movement of 0.20 mm of the whole tooth was expected (Fig. 2B). In order to attain the interactional forces between the aligner and teeth, an aligner based on the targeted dentition was initially generated, and then the aligner with the original dentition was assembled. By utilizing the aligner, the teeth were pushed to move towards their target position due to minor deviations between them. Finally, the system reached an instant equilibrium state through the movement of the teeth and the aligner deformation, during which the orthodontic forces were gradually produced. Actually, this methodology was aimed to simulate the actual process of wearing clear aligners.

Parameters

After imposing the above-mentioned conditions, finite element analysis was performed on the right maxillary central incisor using ABAQUS 2018 (Dassault Systèmes, Vélizy-Villacoublay, France). The prominent indicators of the right maxillary central incisor included the contact pressure distribution of the crown, initial displacements of the mesial incisal corner, midpoint of incisal edge and distal incisal corner, initial rotation around the X-axis, and von Mises stress of the PDLs.

Additionally, the moment-to-force ratio (M/F) and the torque loss per unit of crown displacement (TL/CD) were introduced to appropriately elucidate the behavior of the translational movement along the Y-axis. The factor M_x/F_y represents the ratio of the moment about the X-axis (M_x) to the force along the Y-axis (F_y) acting on the center of resistance (C_{Res}). Similar to the M/F theory in conventional orthodontics, M_x/F_y explains the behavior of tooth movement along the Y-axis. The M_x/F_y value close to zero indicates that the tooth moves almost bodily while a larger M_x/F_y reveals a less proportion of the translational movement.

The ratio of TL/CD is evaluated by:

$$\frac{\mathrm{TL}}{\mathrm{CD}} = \frac{\begin{array}{c}\text{rotation around}\\ \text{the } x-\text{axis } (^\circ)\end{array}}{\begin{array}{c}\text{displacement of the midpoint}\\ \text{of incisal edge along the } y-\text{axis } (\mathrm{mm})\end{array}}$$

in which TL/CD describes the amount of the translational movement from a more clinical perspective where we concern about how much torque loses to reach a desired crown displacement. The higher ratio of TL/CD suggests that a tooth loses more torque to achieve a certain crown displacement in its labiolingual translation movement, and vice versa.

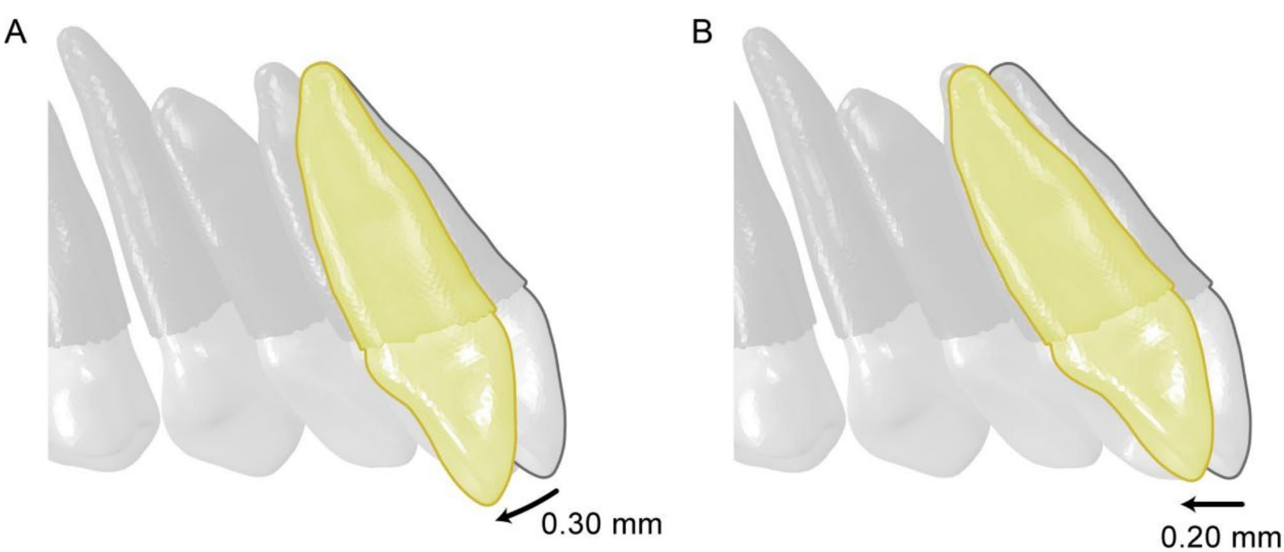

Fig. 2 Illustration of the applied movement. (**A**) Palatal tipping movement, with a 0.30 mm displacement of incisal edge. (**B**) Palatal translational movement, with a 0.20 mm displacement of the whole tooth

Results

Tipping movementwithout attachment

The contact pressure distribution patterns on the crown of the maxillary central incisor were similar across the SCC-NA, NCC-NA and LCC-NA groups under tipping movement loading conditions. Specifically, these patterns were concentrated near the labioincisal edge, particularly at the mesial and distal incisal corners (Fig. 3A).

In all three groups, the incisors exhibited tipping movement palatally along the Y-axis, with the crown moving palatally and the root apex moving labially (Table S1). The results indicated that crown displacement increased with increasing clinical crown lengths, as evidenced by the marker points on the incisal edge (Fig. 3B). Notably, the LCC-NA group exhibited higher rotations around the X-axis compared to the SCC-NA group, suggesting a more significant tipping movement in the LCC-NA group (Fig. 3C).

The von Mises stress distribution patterns in the periodontal ligament were broadly similar across all three groups, with concentrations at the palatal cervical third of the root and the root apex (Fig. 3D). The LCC-NA group exhibited the highest maximum von Mises stress (0.089 MPa), followed by the NCC-NA group (0.081 MPa) and the SCC-NA group (0.070 MPa). The results revealed that the maximum von Mises stress increased with increasing clinical crown lengths, correlating with the degree of tipping movement.

To conclude, in tipping movement, different clinical crown lengths can affect patterns among groups, with longer clinical crowns exhibiting enhance the efficiency.

Translational movementwithout attachment

The contact pressure distribution patterns on the crown of the maxillary central incisor were primarily concentrated at the labial incisal edge and cervical area of the crown across the SCC-NA, NCC-NA and LCC-NA groups under palatal translational movement loading conditions (Fig. 4A).

In all three groups, the incisors exhibited uncontrolled palatal tipping movement during palatal translational movement, suggesting that it was challenging to maintain pure translational movement due to the torque generated by the clear aligner (Table S2). The results indicated that crown palatal displacement increased with increasing clinical crown lengths, while root labial displacement decreased (Fig. 4B and C).

Furthermore, M_x/F_y and TL/CD values were analyzed. The M_x/F_y ratio of the SCC-NA group was the lowest among all three groups (9.90, 10.89, and 11.7 mm, respectively, for SCC-NA, NCC-NA, and LCC-NA). This implied that the SCC-NA group was more likely to achieve translational movement along the Y-axis than the LCC-NA group (Fig. 4D). However, the values of TL/CD decreased with increasing clinical crown lengths (Fig. 4E), which indicating that the LCC-NA group lost less torque to achieve a certain crown displacement in translational movement compared to the SCC-NA group.

The von Mises stress distribution patterns in the periodontal ligament were broadly similar across all three groups, with concentrations at the palatal cervical third of the root and the root apex. The maximum von Mises stress values for each group were similar, suggesting that the maximum von Mises stress was independent of clinical crown lengths in translational movement (Fig. 4F).

To conclude, in translational movement, different clinical crown lengths can affect patterns among groups, with longer clinical crowns having a greater tendency to tip, while shorter clinical crowns are more likely to move bodily. However, longer clinical crowns experience less torque loss to achieve the desired crown displacement.

Effect of attachment in tipping movement

The contact pressure distribution patterns on the crown of the maxillary central incisor were similar across the SCC, NCC and LCC groups under tipping movement loading conditions (Fig. 5A). Specifically, these patterns were concentrated at the attachment, as well as the mesial and distal incisal corners labially in the SCC-LA, NCC-LA and LCC-LA groups. Additionally, in the SCC-PA, NCC-PA, LCC-PA, SCC-LPA, NCC-LPA and LCC-LPA groups, the patterns were concentrated at the attachment and the mesial incisal corner. These findings underscored the influence of attachment design on the contact pressure distribution during tipping movement.

In all groups, the incisors exhibited tipping movement palatally along the Y-axis, with the crown moving palatally and the root apex moving labially (Table S3 and Table S4). Notably, the LCC with attachments groups (LCC-LA, LCC-PA and LCC-LPA) exhibited higher crown displacement along the Y-axis and rotations around the X-axis compared to the SCC with attachments groups (SCC-LA, SCC-PA and SCC-LPA), suggesting a more significant tipping movement in the LCC with attachments groups (Fig. 6A and B). Moreover, the crown displacement and rotation of the SCC-LPA, NCC-LPA and LCC-LPA groups were the highest among all groups, while the SCC-NA, NCC-NA and LCC-NA groups were the lowest. These results indicated that attachments resulted in more significant tipping movement compared to no attachment, and the labio-palatal attachments resulted in the most significant tipping movement.

The von Mises stress distribution patterns in the periodontal ligament were broadly similar across all groups, with concentrations at the palatal cervical third of the root and the root apex (Fig. 7A). Especially, the LCC with attachments groups (LCC-LA, LCC-PA and LCC-LPA)

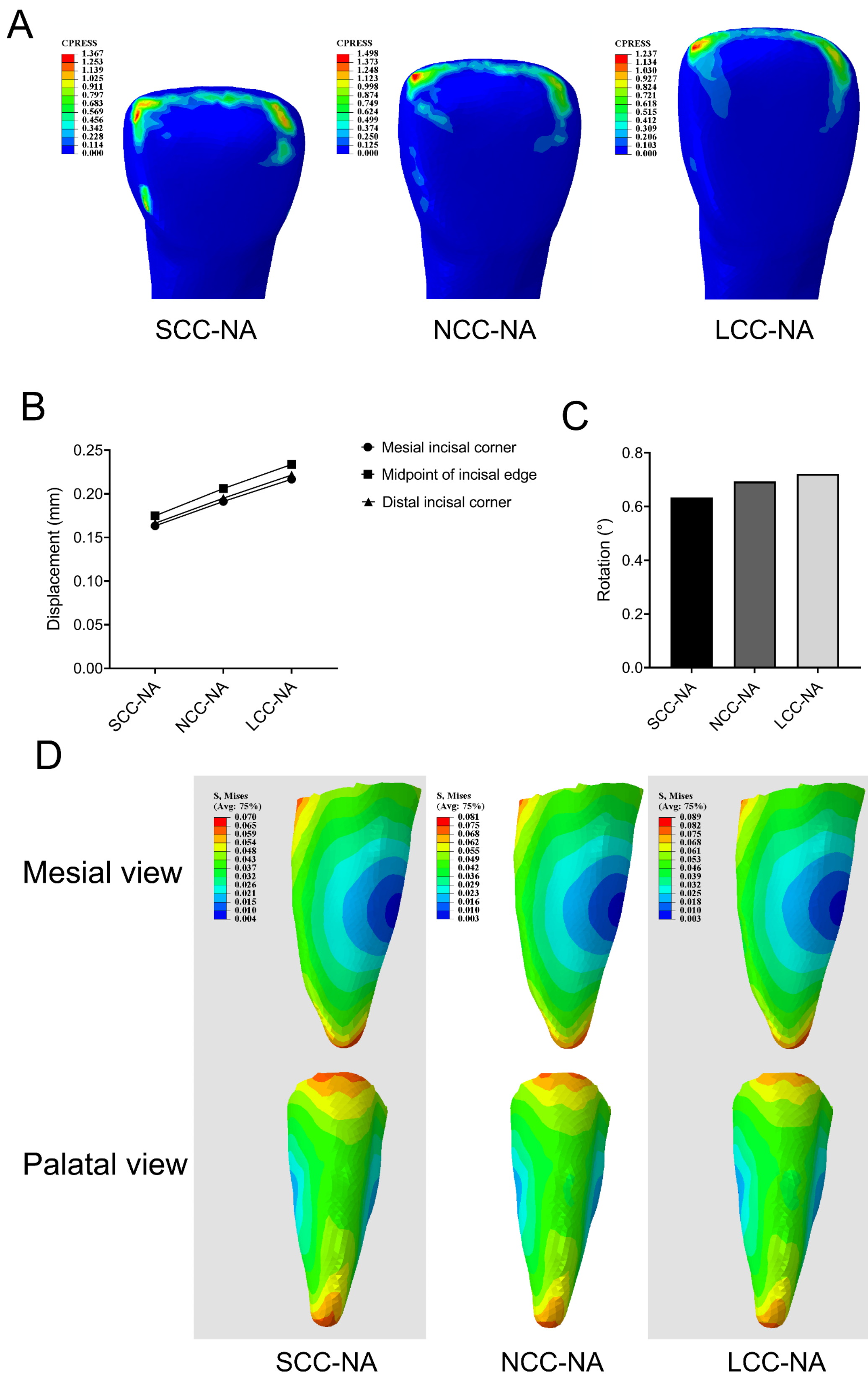

Fig. 3 Contact pressure distribution patterns, crown displacement, rotation and von Mises stress distribution in tipping movement among groups. (**A**) Contact pressure distribution on the crown in the frontal view. (**B**) Graphical representation of displacement of marker points on the incisal edge along the Y-axis. (**C**) Graphical representation of rotation around the X-axis. (**D**) Von Mises stress distribution of PDL. The maximum value on the left scale of the von Mises stress distribution patterns represents the maximum von Mises stress

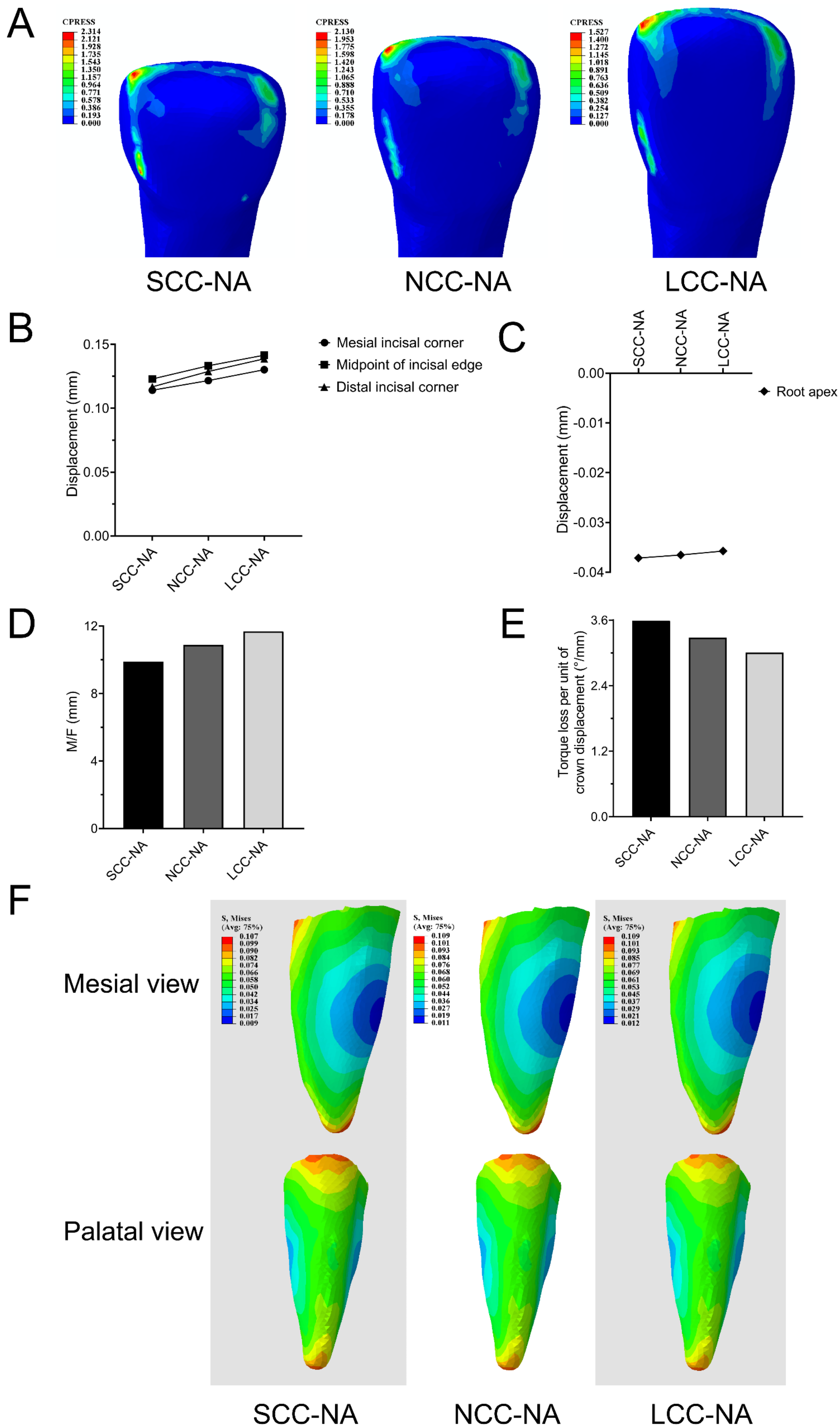

Fig. 4 (See legend on next page.)

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Fig. 4 Contact pressure distribution patterns, crown and root apex displacement, M_x/F_y and TL/CD values, and von Mises stress distribution in translational movement among groups. (**A**) Contact pressure distribution of the crown in the front view. (**B**) Graphical representation of displacement of marker points on the incisal edge along the Y-axis. (**C**) Graphical representation of root apex displacement along the Y-axis. (**D**) Graphical representation of M_x/F_y values. (**E**) Graphical representation of TL/CD values. (**F**) Von Mises stress distribution of PDL. The maximum value on the left scale of the von Mises stress distribution patterns represents the maximum von Mises stress

exhibited higher maximum von Mises stress than the SCC with attachments groups (SCC-LA, SCC-PA and SCC-LPA) (Fig. 7C). Moreover, the SCC-LPA, NCC-LPA and LCC-LPA groups exhibited the highest maximum von Mises stress, while the SCC-NA, NCC-NA and LCC-NA groups were the lowest. These results were consistent with the observed displacement patterns, indicating that both clinical crown lengths and attachments significantly influenced the maximum von Mises stress in the periodontal ligament.

To conclude, in tipping movement, adding different attachments can affect patterns among groups, with the labio-palatal attachments exhibiting the highest effect.

Effect of attachment in translational movement

The contact pressure distribution patterns on the crown of the maxillary central incisor were similar across the SCC, NCC and LCC groups under translational movement loading conditions (Fig. 5B). Specifically, these patterns were concentrated at the attachment, the labial mesial edge and mesial and distal incisal corners in the SCC-LA, NCC-LA and LCC-LA groups. Additionally, in the SCC-PA, NCC-PA and LCC-PA groups, the patterns were concentrated at the incisal edge and labial mesial edge. In the SCC-LPA, NCC-LPA and LCC-LPA groups, the patterns were concentrated at the attachment.

In SCC, NCC and LCC with attachments groups, the incisors still showed uncontrolled tipping movement palatally along the Y-axis under translational movement loading conditions, with the crown moving palatally and the root apex moving labially (Table S5 and S6). Particularly, the LCC with attachments groups (LCC-LA, LCC-PA and LCC-LPA) exhibited higher crown displacement palatally and lower root apex displacement labially compared to the SCC with attachments groups (SCC-LA, SCC-PA and SCC-LPA), suggesting a more significant translational movement in the LCC with attachments groups (LCC-LA, LCC-PA and LCC-LPA) (Fig. 6C and D). Additionally, the crown displacement of the SCC-LPA, NCC-LPA and LCC-LPA groups were the highest among all groups, while the SCC-NA, NCC-NA and LCC-NA groups had the lowest crown displacement, indicating that attachments resulted in increased crown displacement palatally compared to no attachment. The SCC-LPA, NCC-LPA, LCC-LPA, SCC-LA, NCC-LA and LCC-LA groups decreased root apex displacement labially compared to SCC-NA, NCC-NA and LCC-NA groups. However, the SCC-PA, NCC-PA and LCC-PA groups increased root apex displacement labially. These results indicated that the labio-palatal attachments resulted in the most significant translational movement.

The M_x/F_y and TL/CD tendency of the SCC, NCC and LCC with attachments groups were similar to the SCC-NA, NCC-NA and LCC-NA groups (Table S7). Specifically, the SCC with attachments groups (SCC-LA, SCC-PA and SCC-LPA) had the lowest M_x/F_y value, and the LCC with attachments groups (LCC-LA, LCC-PA and LCC-LPA) had the lowest TL/CD value (Fig. 6E and F). Moreover, the SCC, NCC and LCC with attachments groups showed decreased M_x/F_y and TL/CD values compare to SCC-NA, NCC-NA and LCC-NA groups, and SCC-LPA, NCC-LPA and LCC-LPA groups had the lowest M_x/F_y and TL/CD values among all groups. These results indicated that the labio-palatal attachments significantly influenced translational movement.

The von Mises stress distribution patterns in the periodontal ligament were broadly similar across all groups, with concentrations at the palatal cervical third of the root and the root apex (Fig. 7B). The SCC-LPA, NCC-LPA and LCC-LPA groups showed the highest maximum von Mises stress among all groups, while the SCC-NA, NCC-NA and LCC-NA groups had the lowest (Fig. 7D). These results were consistent with the observed results in displacement, M_x/F_y and TL/CD, indicating that labio-palatal attachments significantly influenced translational movement.

To conclude, in translational movement, adding different attachments can affect patterns among groups, with the labio-palatal attachments exhibiting the highest effect.

Discussion

In this study, we performed a finite element analysis and observed that clinical crown length has considerable influences on the efficiency, movement behavior, and maximum von Mises stress of the periodontal ligament in the sagittal movement of maxillary center incisor in clear aligner treatment. Moreover, attachments have also influence on the movement efficiency of the incisor.

Clinical crown dimensions include clinical crown length, width, and buccolingual diameter. Among these factors, clinical crown length has the most widespread distribution in populations with multiple influence factors including congenital morphology, continuous eruption, and gingival recession. Previous study showed an average of 0.3 mm growth per ten years for the anterior

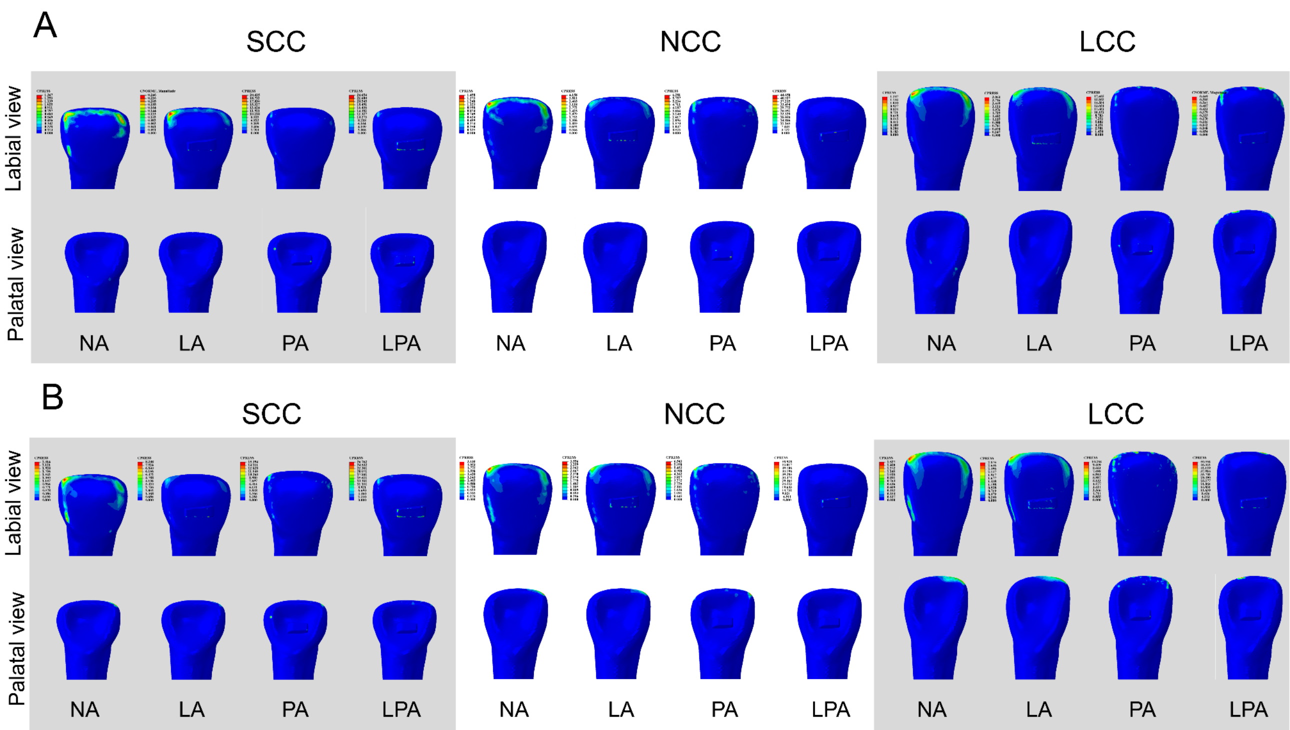

Fig. 5 Contact pressure distribution patterns on the crown in tipping and translational movement. (**A**) Tipping movement in the labial and palatal view. (**B**) Translational movement in the labial and palatal view

tooth length in adults [23]. For adolescents, a greater growth of clinical crown length accompanied by an increase of the standard deviation was reported [17]. Furthermore, the gingival recession caused by periodontitis lengthens clinical crowns [24].

Different clinical crown lengths will affect orthodontic treatment in multiple ways with the most important being the change in center of resistance (C_{Res}). Accurately identifying the center of resistance is becoming increasingly important for predicting effective dental movement during orthodontic treatment. The controlled translational movement of teeth can only be achieved by applying orthodontic force or equivalent torque through the center of resistance of the tooth to the crown. Regardless of the type of orthodontic appliance, the relationship between orthodontic force, equivalent torque, and center of resistance determines the way teeth move, especially during the process of anterior tooth retraction in extraction cases.

In palatal tipping movement, we found that the forces exerted by a clear aligner are concentrated near the labio-incisal edge. Thereby, the maxillary central incisors with longer clinical crowns are more efficient to tip with a longer moment arm. This finding coincides with previous study which also indicated that longer clinical crowns had a longer moment arm to C_{Res}, increasing the moment and aiding tipping movement [25].

By evaluating the biomechanical changes, FEA is able to offer precise measurements of stress distribution within the periodontal tissues that are otherwise impossible to achieve through in vivo methods alone [26, 27]. Stress distribution within the periodontal tissues is a crucial factor of periodontal bone remodelling, and ultimately influences tooth movement. In the current study of palatal tipping movement, it was found that with increasing clinical crown length, the maximum von Mises stress also increased. Since von Mises stress in PDL concentrated in the alveolar crest and root apex for all groups, aligning with previous research [28], it is crucial to consider the impact of the clinical crown length on periodontal health in the clear aligner treatment. Heightened stress within the periodontal tissues may exacerbate the risk of periodontal damage (especially the decreased level of alveolar crest) and potentially lead to root resorption [27, 29], which will prohibit efficient tooth movement.

As to translational movement, it demands greater torque control than tipping, and clear aligners are commonly not appropriate at it [12]. Clinical studies have shown that incisors don't move bodily as programmed, with the accuracy of translational movement by clear aligners being around 50% [3, 30]. Herein, we also explored how the clinical crown length could affect labiolingual translational movement efficiency. In comparison with the tipping movement, we found that forces were concentrated on the cervical crown area, indicating

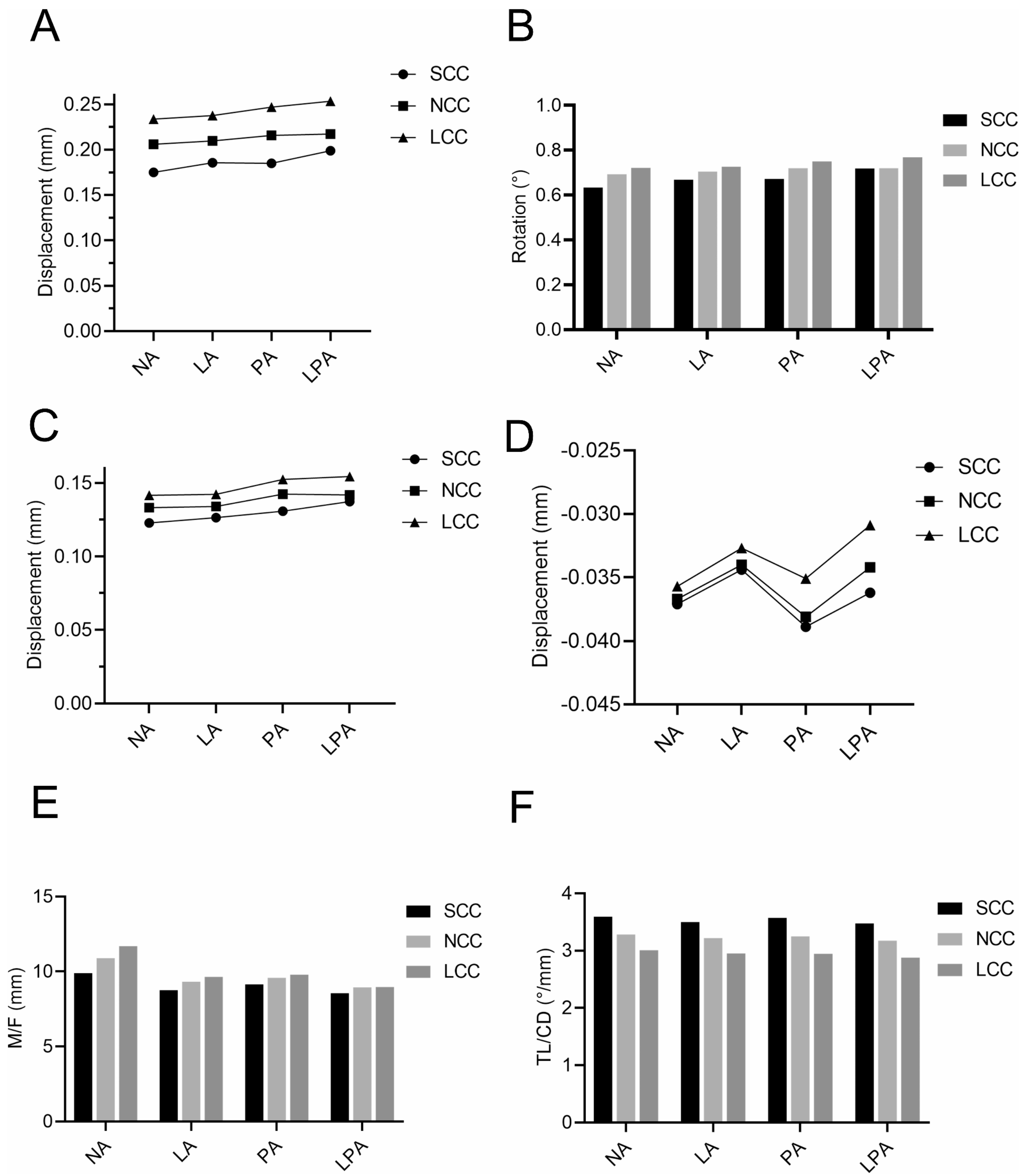

Fig. 6 Crown displacement, rotation in tipping movement and crown and root apex displacement, M_x/F_y and TL/CD values in translational movement. (**A**) Crown displacement along the Y-axis in tipping movement. (**B**) Rotation around the X-axis in tipping movement. (**C**) Crown displacement along the Y-axis in translational movement. (**D**) Root apex displacement along the Y-axis in translational movement. (**E**) M_x/F_y values in translational movement. (**F**) TL/CD values in translational movement

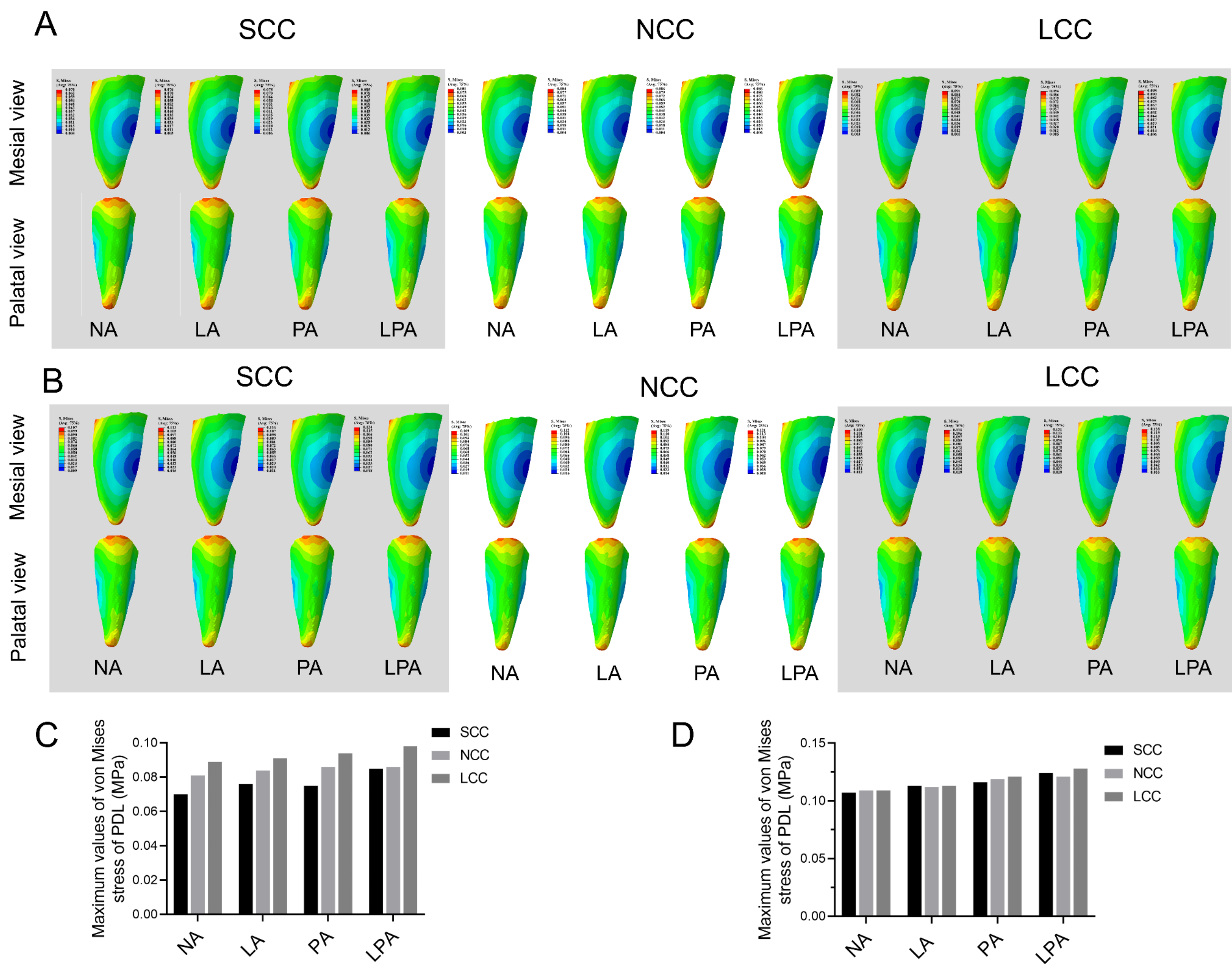

Fig. 7 Von Mises stress of PDL in tipping and translational movement. (**A**) Von Mises stress distribution of PDL in tipping movement. (**B**) Von Mises stress distribution of PDL in translational movement. (**C**) Graphical representation of maximum values of von Mises stress of PDL in tipping movement. (**D**) Graphical representation of maximum values of von Mises stress of PDL in translational movement. The maximum value on the left scale of the von Mises stress distribution patterns represents the maximum von Mises stress

a shorter moment arm. It was also demonstrated that LCC groups exhibited the highest anteroposterior incisal edge displacement, suggesting longer clinical crowns enhanced translational efficiency.

To investigate the mechanism of enhanced incisal edge displacement with longer clinical crowns, we further analyzed their displacement behaviors. Consistent with Jiang et al. [31], our study indicated that all groups showed labial displacement of root apex, with the LCC groups exhibited the least root apex displacement, indicating a more "relatively palatal" movement. To better describe these displacement behaviors, we introduced the TL/CD ratio. Unlike previous studies that used torque loss or rotation around the X-axis and M/F ratio to quantify bodily movement [32–34], the TL/CD ratio accounts for differences in crown length, as varying crown lengths lead to different rotational radii. This ratio also aligns with clinical reality, showing how much torque is lost for the same crown displacement. The results showed that the LCC groups had the lowest TL/CD, indicating it lost the least torque for the same crown displacement, while the SCC groups had the highest TL/CD, losing the most torque in the palatal movement of the maxillary central incisor.

Classical orthodontic biomechanics uses the moment-to-force ratio at the bracket to determine tooth movement types [35]. However, since clear aligners apply force over a broader area than brackets [34], analyzing moments and forces at the crown is challenging. In this study, forces on the teeth were replaced with moments and forces on C_{Res}, and the ratio M_x/F_y provided information about how the tooth would move along the Y-axis. The results showed the SCC group had the lowest M_x/F_y, followed by the NCC and LCC groups (Fig. 4D), suggesting that the LCC and SCC groups had the most tipping and bodily movements, respectively. In other words, shorter clinical crowns facilitated palatal translational movement of the maxillary central incisor.

It seems to be contrary to our common orthodontic sense and previous results about TL/CD where incisors with short clinical crowns lose the most torque. Geometrically, longer clinical crowns are more prone to tipping, aligning with M_x/F_y results. However, longer incisors have a longer radius of rotation from incisal edge to C_{Res}, allowing for more crown displacement from rotation around the X-axis (torque loss). Thus, while longer crowns involve less translational movement, they can still achieve the desired crown displacement with less torque loss from a clinical viewpoint.

During translational movement, the von Mises stress distribution in the PDL resembled that in tipping movement. However, the maximum von Mises stresses were similar across all groups. This can be explained by the increased tipping movement with longer crowns, which concentrated stress at the cervical and root apex regions while reducing the palatal bodily movement of the entire root. These two effects cancelled out each other and therefore led to similar maximum von Mises stresses.

For the effect of attachment in clear aligner treatment, previous studies highlight the complexity of controlling corrective forces with clear aligners, where attachment design and placement are crucial [36]. Attachments were believed to enhance tooth movement effectiveness by increasing force transfer and aligner retention [12, 37]. In our study of palatal tipping movement, horizontal rectangular attachments were found to increase crown displacement and rotation, enhancing tipping movement effectiveness. As to translational movement, adding attachments improved crown palatal movement in all groups. Labio-palatal and labial attachments reduced root apex displacement, suggesting that they had the higher tendency to 'relatively palatal' displacement. Other studies aldo showed that attachments promote tooth bodily movement and prevent uncontrolled tipping without torque control [38–40]. Moreover, our results demonstrated that the incisor with labio-palatal attachment had the lowest M_x/F_y and TL/CD values, indicating it was most likely to achieve bodily movement. This finding is similar to Fan et al. [41] which showed that bucco-palatal attachment reduced uncontrolled buccal or palatal tipping.

Understanding the influence of clinical crown length on orthodontic tooth movement in clear aligner therapy is essential for optimizing biomechanical efficiency, ensuring proper anchorage, accurate treatment planning, minimizing risks, customizing treatment, achieving predictable outcomes, and maintaining periodontal health. This knowledge enables orthodontists to provide more effective and safer treatments for their patients. Nevertheless, there still are potential limitations of our study:

First, although finite element analysis is a powerful tool to assess the force system of orthodontic treatments, FEA relies on a simplified model of the actual physical system. This simplification can cause the model to differ from reality, especially when dealing with complex orthodontic tooth movement and the periodontal environment. Therefore, we need to interpret the currently results objectively and more high-quality clinical explorations should be brought about to validate the results. Second, the crown length was based on an estimated value derived from a convenient review of published studies rather than a systematic review or meta-analysis. Tooth models were established based on epidemiological evidence in this study. Despite ample data on clinical crown length distribution, no exact diagnostic criteria define long or short clinical crown length. The taken values of long or short clinical crown length come from the upper or lower limit of the reference range, based on the reported clinical crown length data. Third, as reported that there is a regular length-to-length ratio among clinical crowns of maxillary central incisors, lateral incisors, and canines [13], however, in the current study, we just studied the change of a single incisor's clinical crown in the present work. Further studies are still required to examine the impact of the whole anterior teeth.

Therefore, the suggested future promising directions of studies include: conducting a clinical trial based on determining and grouping typical patient of short, normal or long incisors, and collect comprehensive information about different type of tooth movement of various clinical crown lengths using clear aligners in reality.

Conclusions

- Clinical crown length can impact the effectiveness of maxillary central incisor in tipping and translational movement.
- Longer clinical crowns enhance the efficiency of tipping movement due to a longer moment arm.
- Longer clinical crowns have a greater tendency to tip in translational movement, while shorter clinical crowns are more likely to move bodily.
- Longer clinical crowns experience less torque loss to achieve the desired crown displacement in translational movement.
- The maximum von Mises stress in PDL has a slight positive relationship with the clinical crown length in tipping movement.
- Labio-palatal attachments have the optimal effect in tipping and translational movement.

Abbreviations

CCL	Clinical crown length
C_{Res}	Center of resistance
CT	Computer tomography

F_y	Force along the Y-axis
LA	Labial attachment
LPA	Labio-palatal attachment
LCC	Long clinical crown
LRL	Lower reference limit
M_x	Moment about the X-axis
M/F	Moment-to-force ratio
M_x/F_y	Ratio of the moment about the X-axis to the force along the Y-axis
NA	No attachment
NCC	Normal clinical crown
PA	Palatal attachment
PDL	Periodontal ligament
SCC	Short clinical crown
SD	Standard deviations
TL/CD	Torque loss per unit of crown displacement
URL	Upper reference limit

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

Supplementary Material 4

Supplementary Material 5

Supplementary Material 6

Supplementary Material 7

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Not applicable.

Author contributions
CZ: contributed to conceptualization, methodology and original draft preparation; ZF: contributed to study conception, data analysis and original draft preparation; JR: contributed to study design and analysis and original draft preparation; HL, HI, RL, YQ: contributed to software and data curation; YG, BG, ZH: data contributed to acquisition; YC, WW: contributed to project administration, supervision, and manuscript review and editing. All authors have read and approved the manuscript.

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Data availability
Availability of data and materialsThe datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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