



Biomechanical influence of anchorages on orthodontic space closing mechanics by sliding method

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Abstract

This study aims to analyse the stress distributions and initial displacements of teeth during the space closing stage through a three-dimensional finite element method. Computed tomography images of a patient were used to reconstruct the detailed teeth and alveolar bone, and brackets with stainless steel archwire were modelled according to the orthodontic prescriptions. The second premolars and first molars were chosen as the anchorages in the model 6-force, with buccal tubes attached to the second molars in the model 6-force-7, and the second molars as additional anchorages in the model 7-force. The results indicated that a movement of lingual lateral inclination occurred on the incisors during the retraction, and the frictional force between the teeth and the archwire significantly reduced the stress on the teeth and periodontal structures.

Keywords Teeth retraction · Space closure · Finite element analysis (FEA) · Periodontal structures · Anchorage

1 Introduction

Malocclusion is one of the most common issues in dentistry with high prevalence and a need for orthodontic treatment. It has been reported that the general prevalence of malocclusions can be 71% from primary to early permanent dentition [1]. More than 20% of the children investigated had a need for severe or extreme orthodontic treatment [1]. The extraction of the first premolar teeth was usually necessary at the beginning of the treatment, and a straight wire appliance together with sliding mechanics was used to close the space at the end of the treatment. Here, biomechanics plays an integral role in the process and is the key to understanding the interaction between the force system

generated by the orthodontic appliance and the dental system. Many studies [2–14] have been conducted out to analyse the stress and strain profiles in teeth, periodontal ligament (PDL), and alveolar bone with the forces applied in the orthodontic appliances. It is well known that biomechanical studies in orthodontics can aid in optimising the efficient movement of teeth.

The finite element method (FEM) is an effective computer-simulation tool in solving stress-strain problems in the mechanics of solids and structures [15]. It has been introduced as one of the numerical analyses techniques for precise conclusions in many fields, including orthodontics. In some cases, FEM was applied to simulate orthodontic tooth movements involving absorption and apposition of the alveolar bone [2, 3, 6, 9, 10]. However, FE models in numerous investigations have been constructed with a single tooth to analyse the stress-strain distributions [4, 5, 11–13] or the tooth movement [2, 3, 6, 9, 10]. Certainly, the loads on the teeth in the orthodontic treatment were different from the loads assumed on a single tooth; thus, brackets are the most crucial part of the orthodontic appliance in the whole procedure. It is a point of interest for orthodontists to gain knowledge regarding the accuracy of brackets, which deliver the orthodontic forces for certain movements [16, 17]. Therefore, related studies were conducted to determine the loads on the brackets or the frictional force between the wire and the brackets [18, 19].

Brackets, dentition and periodontal tissues were taken into consideration in some recent models. The effects of some

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parameters, such as the position and length of the power arm [20, 21], magnitude of applied force and frictional coefficient [7], position and height of the mini-implant and anterior retraction hook [22], and magnitude of applied torque [23], have been discussed with respect to the retraction of anterior teeth using sliding mechanics. However, dentin, enamel, and pulp were not separated from each other in the teeth models, which may lead to remarkable stress deviation in the roots according to the related research [24]. Moreover, the teeth were even assumed to be rigid bodies in some studies [7, 21]. Several models only contained six anterior teeth [21] or half of the dentition [7], and neglected the interaction between the brackets and archwire [2, 3]. These simplifications undoubtedly influence the accuracy of the results.

The selection of the anchor teeth was another dilemma for orthodontists. The orthodontic force in the first molar may not provide adequate anchorage, whereas the use of second molars as an anchor may lead to high frictional force between the brackets and the archwire. The maximisation of the tooth movement and the minimisation of undesirable side effects, such as root resorption, pain, pulpal changes, periodontal disease, and temporomandibular dysfunction, were desired [25, 26].

In this study, three-dimensional (3D) FE models, including the Roth prescription appliance, teeth, PDL, and alveolar bone were constructed to investigate the initial displacement of the tooth and the distribution of stress during the space closing stage using a straight wire appliance, and the preference of the selection of the anchorages was discussed.

2 Materials and methods

The retraction of the anterior teeth was often used to close the premolar extraction space. The distal sliding of the anterior teeth along an archwire was produced with the help of brackets [18]. 3D FE models of space closing mechanics were developed using the sliding method according to the CT images of a patient during the stage of space closing. The geometries of the teeth (including enamel, dentin, and pulp) and the alveolar bone (including cortical and cancellous bone) were reconstructed using MIMICS 8.1 (Materialise, Leuven, Belgium). Then, the model was exported to ABAQUS 6.6 (ABAQUS, Inc., USA) for the FE analysis. The PDL was simulated as a 0.2 mm layer around the root of the tooth according to the related research [6]. This study was approved by the Affiliated Hospital of Stomatology of Chongqing Medical University (IRB Reference No: CQHS-IRB-2014-01).

According to the orthodontic prescriptions, Roth brackets with a 0.56 mm (0.022 in.) edgewise slot and a 0.46×0.64 mm (0.018×0.025 in.) stainless steel archwire were chosen. All components of the apparatus, including the brackets, buccal tubes, and archwire with retraction hooks, were generated in ABAQUS, as illustrated in Fig. 1 a, c. Then the brackets and buccal tubes were glued to the teeth using

adhesive, which was modelled as a thick layer between the teeth and the brackets or buccal tubes, as shown in Fig. 1 b. And an archwire with retraction hooks (Fig. 1c) were put across the preset slots in brackets and buccal tubes, as shown in Fig. 1 d. In clinical treatments, the coil springs were used to connect the retraction hooks on the archwire with those on the brackets or buccal tubes, so that the springs can apply forces since they were stretched. The coil springs were not modelled in our simulation, and the forces were directly applied on the retraction hooks instead.

The mechanical properties of the dentin, enamel, dental pulp, PDL, cortical and cancellous bone, brackets, archwire, and orthodontic adhesive were assumed to be homogeneous, isotropic, and linearly elastic, as presented in Table 1 [27–31].

Under the orthodontic retraction force, the posterior teeth remained still while the distal movement of the anterior teeth occurred along the archwire. The relative motion between the archwire and the slots produced frictional force which could affect the results for sliding methods. Contact elements were applied to simulate the interaction between the archwire and the bracket slots by setting the frictional coefficient to 0.2 according to a related study [19]. Spring elements were used to connect the brackets and the archwire [8], and the surfaces of both the condyles were restricted to six degrees of freedom (Fig. 1e–g). The magnitude of the retraction force was generally set to be about 1–1.5 N in the clinic during the anterior teeth retraction [32–34]. In this study, three types of loading conditions that involve different anchor selections were simulated: Loads with a magnitude of 1 N, the value of retraction forces applied on the patient's orthodontic appliance, were applied to the retraction hooks and the first molars brackets, without a buccal tube connected to the second molars, named as 6-force (Fig. 1e), and with the archwire across the attached buccal tubes to the second molars, named as 6-force-7 (Fig. 1f). Furthermore, the retraction forces were applied to the hooks and the buccal tubes in the second molars, named as 7-force (Fig. 1g). The number “6” and “7” in the front of “force” represented the teeth on which the retraction forces were applied and the extra “7” in “6-force-7” represented the extra archwire across the attached buccal tubes on the second molars, as the first molars and second molars are noted as “6” and “7” respectively, according to the Palmer notation method.

Only 1 patient data was simulated in the study, which generally was not enough to represent any category or subcategory of malocclusion due to individual differences. However, the process concerned in the study was the anterior teeth retraction, before which the teeth have already been adjusted and the final retraction procedure was to close the space. The differences among the malocclusion types became slight and could be neglected if only mandible was considered. We assumed that the type hardly affected the procedure or the stress and strain distributions and focused only on discrepancies among different loading conditions.

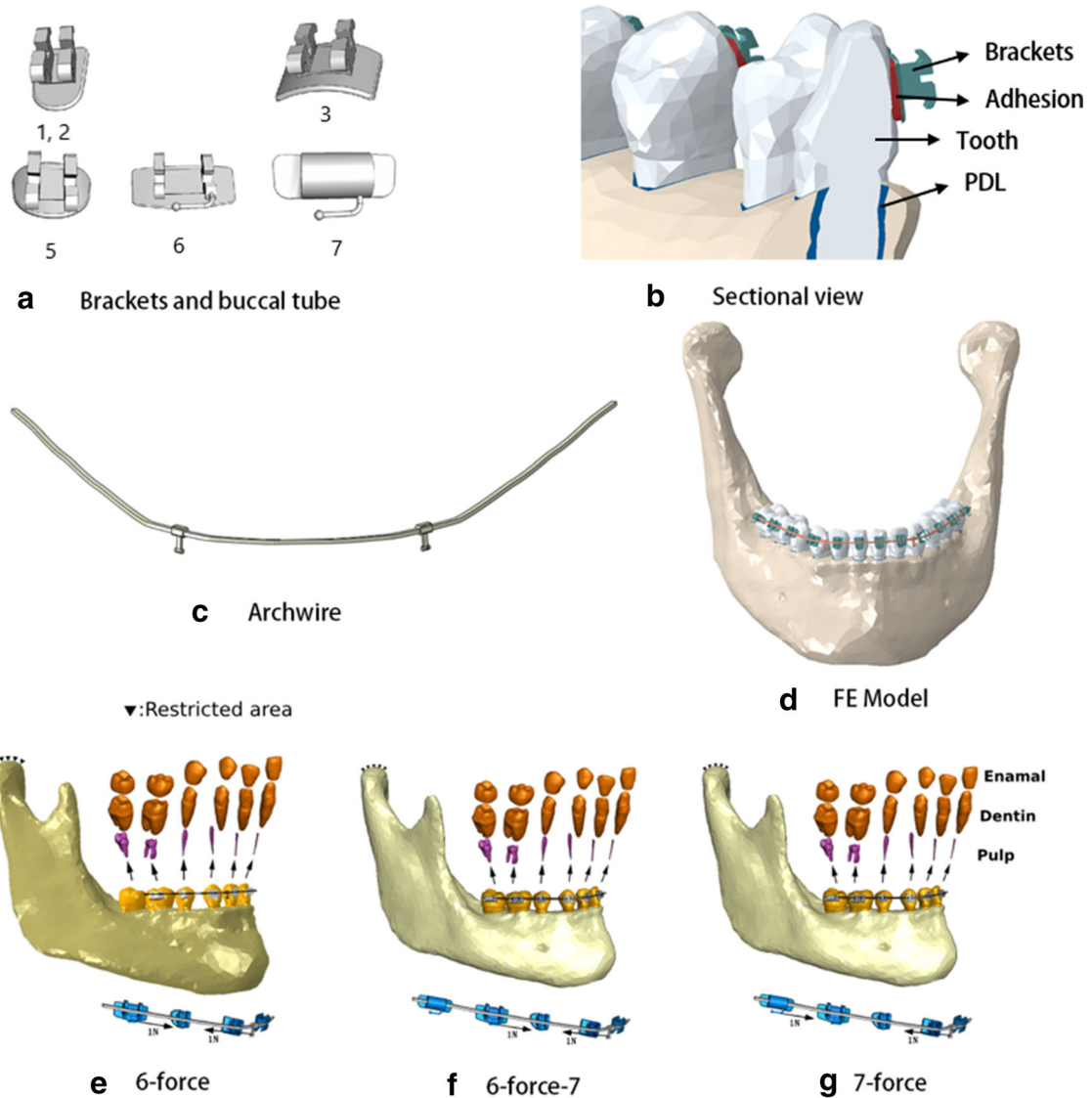


Fig. 1 Appliance and models with loads and boundary conditions applied. **a** Details of the brackets and the buccal tube, “1, 2” was used for incisors, “3” was used for canines, “5” was used for second premolars, “6” was used for first molars, and “7” was used for second molars. **b**

Sectional view of the central incisor and its bracket. **c** The archwire with retraction hooks. **d** Reconstructed FE model. **e** The model 6-force and its loading conditions. **f** The model 6-force-7 and its loading conditions. **g** The model 7-force and its loading conditions

Table 1 Mechanical properties

Material	Young’s modulus (MPa)	Poisson’s ratio
Cancellous bone	7930	0.3
Cortical bone	13,700	0.3
Enamel	84,100	0.3
Dentin	18,600	0.31
PDL	0.68	0.49
Dental pulp	2	0.45
Stainless steel arch wire	176,000	0.3
Roth brackets	210,000	0.3
Orthodontic adhesive	11,721	0.21

3 Results

3.1 Stress distribution

Most of the high stress regions in the three models appeared near the labial side of the anterior teeth, especially in the two central incisors and near the molars on which the forces were applied (Fig. 2). The maximum von Mises stresses of the alveolar bone in 6-force, 6-force-7, and 7-force were 241.3, 231.3, and 226.5 KPa, respectively.

High stress regions appeared in four incisors and the forced teeth, whereas the low stress regions appeared in the second premolars in all cases (Fig. 3). The maximum von Mises stresses of the teeth in 6-force, 6-force-7, and 7-force were

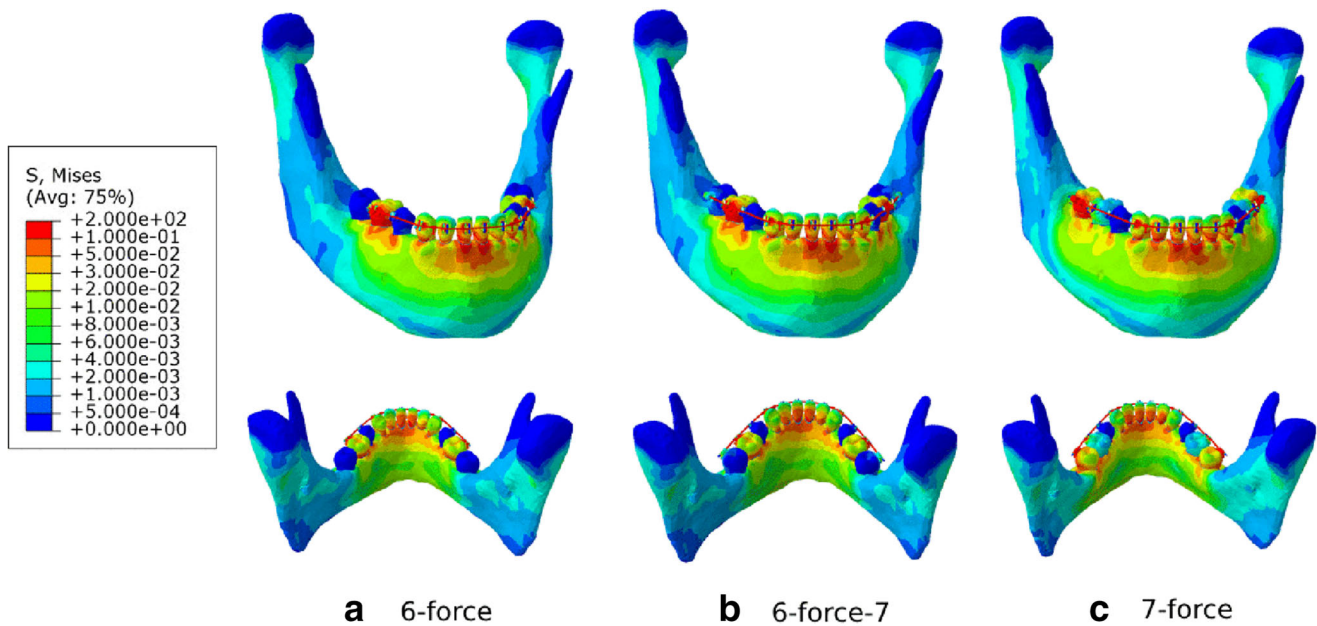


Fig. 2 The von Mises stress distributions in models (MPa)

562.5, 521.2, and 482.3 KPa, respectively; and the von Mises stress in the PDL exhibited almost identical distributions as those of the teeth (Fig. 4).

3.2 Displacement of the teeth

The lingual side tipping displacements occurred in the lateral and central incisors during the process of retraction of the anterior teeth (Fig. 5). The maximum displacements of the teeth in 6-force, 6-force-7, and 7-force models, which occurred in the crown of the incisors, were 2.333×10^{-3} , 2.153×10^{-3} , and 2.703×10^{-3} mm, respectively.

4 Discussion

The models in this study were constructed with high precision to improve the reliability of the conclusions. Related research mentioned that factors, such as the wire size, bracket slot size, interaction between bracket slot and archwire, and variable anatomical parameters, affect the biomechanical behaviour of the tooth movement [20]. The maximum stresses in the PDL of incisors with 14 KPa [7] were notably higher than 3.97 KPa in this study, probably due to the meticulous relationship between the brackets and the teeth on it. The preset torque of the Roth bracket slots induced the angle of labial tipping to remove the lingual tipping movement caused by the

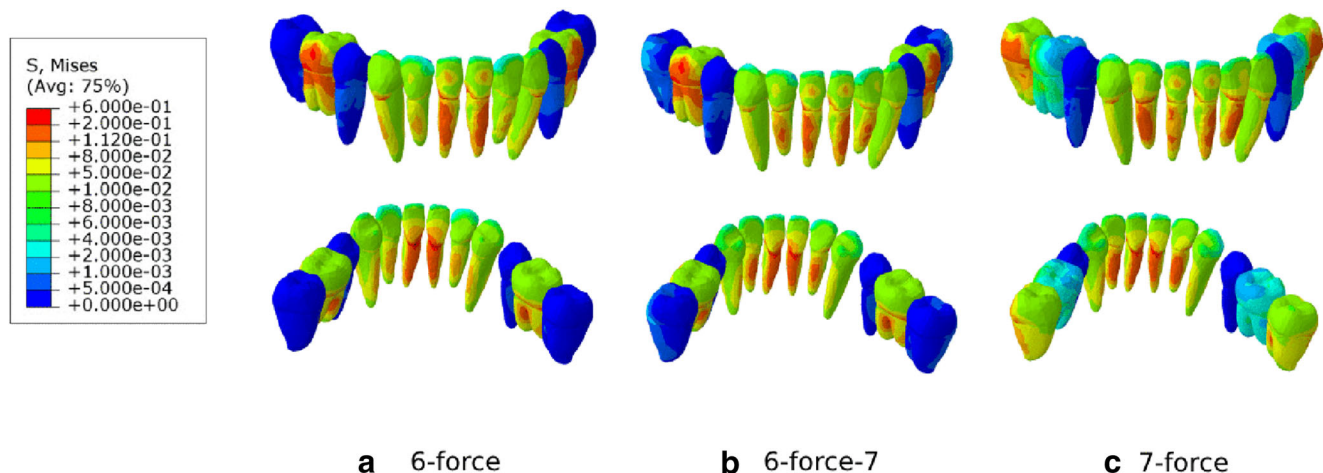


Fig. 3 The von Mises stress distribution in teeth (MPa)

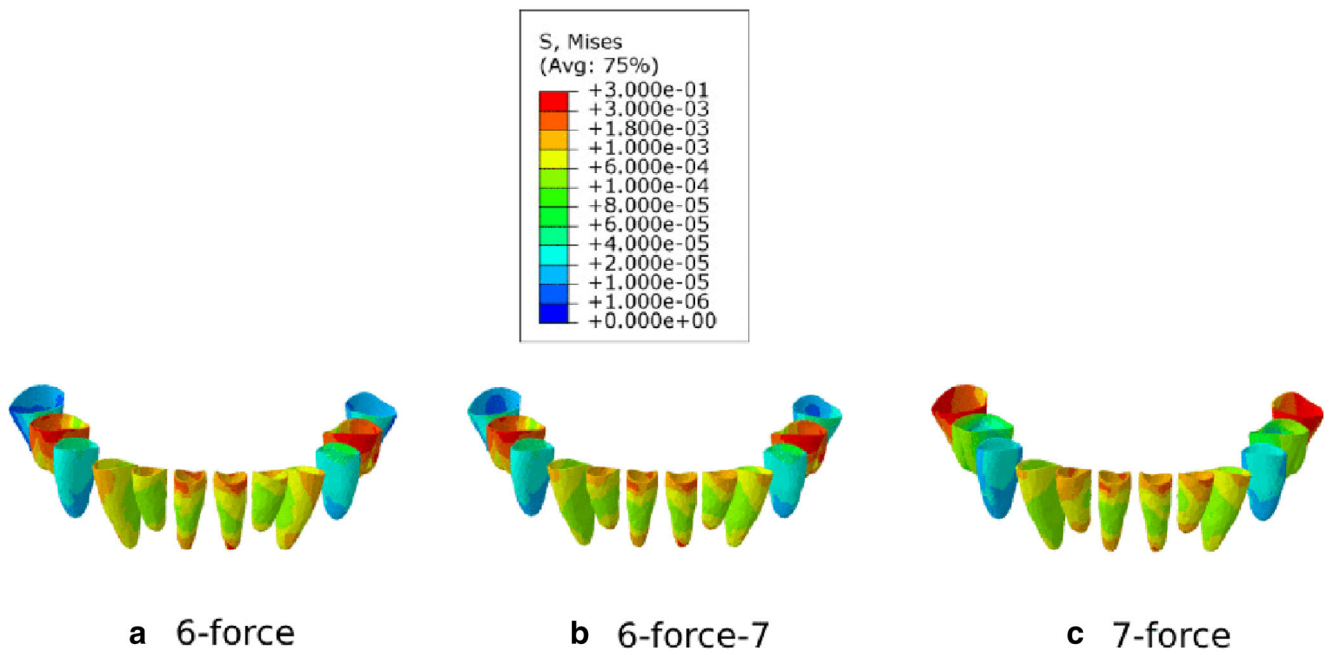


Fig. 4 The von Mises stress distribution in PDL (MPa)

retraction force. Body movement was performed as a result of the refinement of the model to reduce stress in the periodontal tissues. Improving simulation accuracy is essential to obtain more reliable results. However, the results of the study were not directly validated with experimental or clinical data due to many reasons. Limitations of the study are obvious considering the discrepancies between real situations and simulations, which are inevitable in numerical analyses. We rebuilt the models through the original clinical CT images, and the

orthodontic appliance was accurately built. Those improvements of the FE models could narrow the gap and provide accordingly accurate results.

The stress distributions revealed similar patterns between the three simulations, indicating regions of high stress near the incisors, and these regions tended to have a severe apical root resorption after orthodontic treatment. A strong correlation between the root resorption and the high stress could be speculated during the treatment. A related research found that the

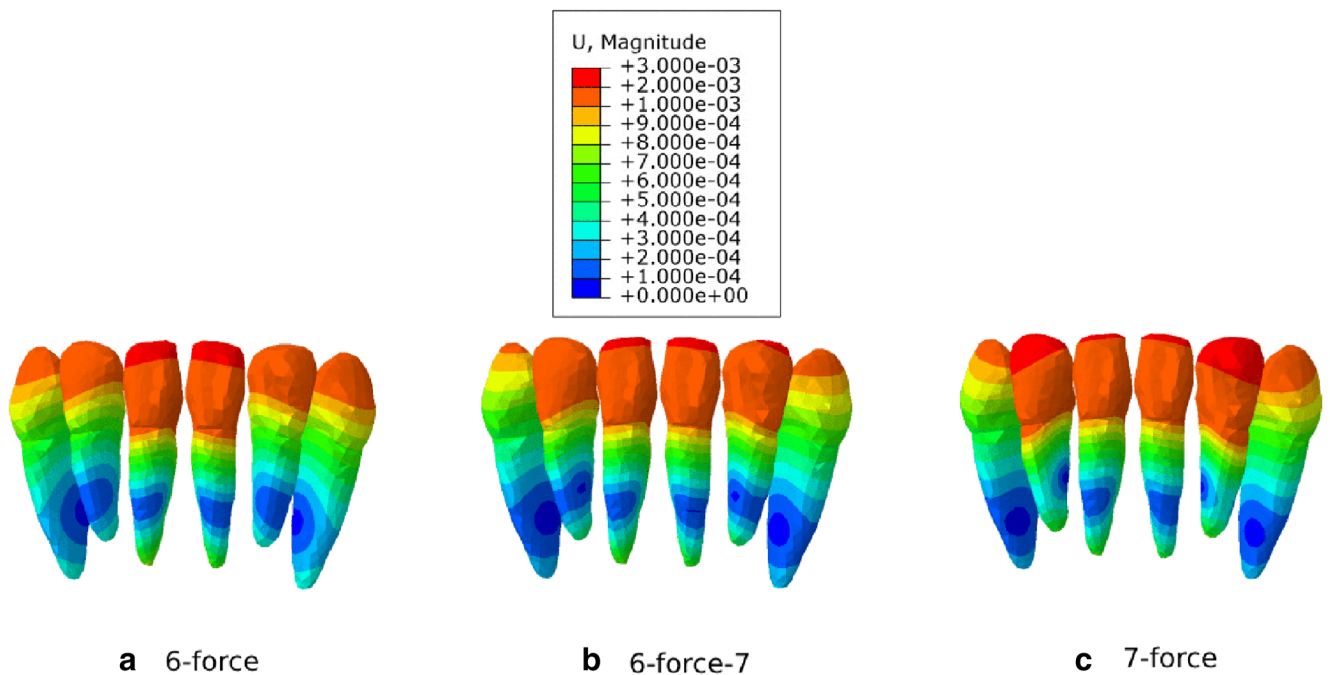


Fig. 5 The initial displacement of six anterior teeth (mm)

risk of root resorption increased when the hydrostatic pressure in the PDL exceeded the typical human capillary blood pressure [35]. The maximum von Mises stresses of the root apex and PDL in the central incisors were greater than those in the lateral incisors. A survey also indicated that the central incisors exhibited a higher percentage of severe root resorption than the lateral incisors of orthodontic treatment [36]. Rare cases with root resorption in canines or molars have been found in the orthodontic treatment process despite the high stress near the root apex. This could be a consequence of the area and the morphological root discrepancy between canines or molars and incisors. The studies [37–40] have shown that thin, tapered, and dilacerated root morphology could lead to higher probability of resorption. A clinical research [41] also found that pain in the anterior teeth was greater than the posterior teeth. Therefore, the incisors are more prone to resorption. Reduction of the torque applied to the incisors can be taken into consideration in the clinical practice to reduce stress and the possibility of root resorption.

The results of 6-force-7 were evaluated in comparison with those of 6-force. The frictional force in 6-force-7 was greater than that in the 6-force as a result of the appliance configurations. The maximum stresses of the anterior teeth in 6-force-7 were lower than those in 6-force, with nearly a 10% reduction in the root and PDL of the central incisors. The stress discrepancy was significant enough to reveal the imperceptible role of the additional frictional force. It was possible to find a decrease in the maximum stress of the teeth in 7-force with the second molars as anchorage. The stresses turned out to be lower in the central incisors but higher in the lateral incisors in 7-force. This could lead to a more uniform stress distribution during the space closing stage.

The initial displacement of the three models aids in predicting the movement of the teeth during the treatment using the sliding mechanics. The results indicated more displacements in the crown than at the apex of the root when the lingual side tipping occurred in the process, according to the clinical observation [42].

The maximum displacement in 6-force-7 was 7.7%, less than that in 6-force. Increasing the frictional force between the archwire and the bracket slots slowed down the movement of the tooth. The maximum displacement in 7-force was 15.9%, which was higher than that in 6-force; hence, the second molar can be considered to obtain more anchorages and accelerate the retraction of the anterior teeth in clinical practice. The mini orthodontic implant was also considered an option to obtain maximum anchorage during anchorage loss. Because of the individual differences of patients, biomechanical environment can be diverse among them. With the help of patient-specific simulation, orthodontists can predict the outcome precisely, and lower the stress by adjusting the retraction force or changing the appliance if it's higher than expected.

5 Conclusion

Models with high precision were used to simulate the interactions between the teeth and the appliance, based on the reliable response of teeth under the force of retraction. The lingual side tipping movement, as well as the maximum initial displacement, occurred on the incisors during retraction. Additional anchorages increased the frictional force and reduced the stresses in the teeth and the PDL during the process of the anterior teeth retraction. Therefore, it is vital for the magnitude of the anchorages to be carefully considered in simulations and clinical operations. This study can aid doctors in understanding the deep connection between clinical strategies and their outcomes, thereby improving the procedure for the prevention of undesirable side effects.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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