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Original Research Article

Trimline Length as a Variable in Aligner-Based Distalization: A Finite Element Analysis Study

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ABSTRACT

Aim: This study aimed to evaluate the impact of aligner trimline length on the movement of the upper second molar during the distalization process.

Materials and Methods: Two finite element models were developed utilizing different aligner trimline lengths. One model featured a trimline at the gingiva (Mode A1), while the other had a trimline positioned 2 mm above it (Model A2). Both models were applied to a 3D full-toothed maxillary model, excluding the upper third molars. No attachments were applied to the molars. During the simulation, a distal displacement of 0.25 mm was applied to the upper first and second molars. The results regarding von Mises stress associated with the upper second molar and its periodontal ligament, as well as the tooth displacement data, were analyzed.

Results: The stresses in the apical region of the PDL increased with longer trimlines. The crown displayed stress areas mainly on the mesial side in both models. In Model A2, stresses began to extend distally, and the stresses on the roots also increased. Both groups exhibited rotation in the distopalatal direction, and Model A2 showed a greater distal crown displacement.

Conclusion: In the present study, increasing the trimline length was a more effective approach for managing the movement of upper second molar teeth during distalization.

Keywords: Biomechanics; Clear aligners; Distalization; Finite element analysis

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INTRODUCTION

Clear aligners, a popular orthodontic method, correct many malocclusions.[1] Studies state that aligners can easily perform upper molar distalization, a key step in correcting malocclusions.[2-4] Preventing side effects, such as tipping of the distalized tooth, is crucial during distalization in orthodontic treatment. Many mechanics have been developed to counter these unwanted movements in fixed mechanics.[5] There are also studies on clear aligners in this regard.[2-4] In a retrospective study, the researchers evaluated molar distalization, incisor torque, and premolar rotation correction.[3] They found that molar distalization achieved the highest accuracy, with a rate of 87%, compared to the other two movements. In that study, the efficiency and necessity of the use of attachments were also reported. On the other hand, Boyd *et al.*[1] and Schupp *et al.*[6] discussed that correcting class II malocclusion through molar distalization can be achieved without the use of attachments. A retrospective study published in 2016 assessed the distalization of molars using clear aligners. The findings indicated that molars could be distalized with attachments and elastics by 2.25 mm without significant crown tipping or vertical movement.[7] Another study indicated that clear aligners effectively managed the vertical measurements during upper molar distalization. It was also stated that it is an ideal solution for the treatment of hyperdivergent or open bite cases with class II malocclusion.[8]

Many studies assess the impact of using attachments on movement efficiency during clear aligner treatment. Some studies compared movements done without attachments to those done with various attachments.[4,9,10] Other studies aimed to compare specific attachments with each other.[11,12] These studies showed that samples without attachments can move unexpectedly. Using attachments helps achieve the intended movements.[9,10] The effect of the trimline designs of the aligners on their retention and the biomechanics of tooth movements is also being investigated.[13-16] A longer aligner trimline provides more controlled tooth movement.[15] It was also reported that aligners with straight and extended trimlines have better retention and force transmission.[14,17]

Numerous studies used Finite Element Analysis (FEA) to evaluate the biomechanics of aligners.[9,13,18-20] FEA offers a valuable approach to understanding the initial tooth movement following force loading. It is a technique that has gained attraction in biomechanics and shows how existing structures respond to stress and strain from external forces. Also, it is a promising method for simulating tooth displacement patterns in orthodontics.[21,22]

The present study aimed to test the effectiveness of different trimline lengths using FEA and focused on their use in upper molar distalization with aligners, without using any attachments.

MATERIALS AND METHODS

The null hypothesis (H_0) tested in this study was that changing the length of the aligner trim line had no significant effect on the stress distribution and tooth movement during distalization of the upper second molar. In order to test this hypothesis, two different finite element models were created and all parameters except the trimline length were kept constant. One model had an aligner trimline at the gingival margin (Model A1). The other had a trimline 2 mm above it (Model A2). No attachment was applied to the molars. A comparison was conducted between the two models by examining the von Mises stress patterns on the upper first molar and its periodontal ligament (PDL), along with the associated displacement patterns.

Material Properties

Teeth, bone, gingival mucosa, aligner, and attachment structures were assumed to be linear, elastic, homogeneous, and isotropic. Elastic modulus and Poisson's ratio values of the materials are given in Table 1.

The PDL was assumed to be non-linear and had 0.2 mm thickness. The incorporation of the nonlinearity of the PDL has been demonstrated to exert a substantial influence on the outcomes of FEA.[23] The nonlinear static analysis was performed using the implicit solver in LS-DYNA. The PDL was modeled utilizing the second-order Ogden hyperelastic constitutive model, as presented in Table 2.[23] The nonlinearity in the analysis primarily originates from the material formulation. However, additional sources of nonlinearity, such as geometric and contact effects, might also contribute to the overall nonlinear response. Given the incompressibility characteristics of soft biological tissues, appropriate constraints were incorporated into the numerical model to ensure an accurate representation of the PDL's mechanical behavior.

Table 1. Material Properties

COMPONENT	ELASTIC MODULUS (MPa)	POISSON RATE
Cortical Bone	13700	0.3[11]
Cancellous Bone	1370	0.3[11]
Gingiva	3.45	0.45[11]
Teeth	19600	0.3[9]
Aligner	528	0.36[9]

Table 2. Parameters of 2nd Ogden model

$\mu 1$ (MPa)	$\mu 2$ (MPa)	$\alpha 1$
0.005 54	0.11	0.25
$\alpha 2$	$D1$ (MPa)	$D2$ (MPa)
0.12	0.12	0.97

Modelling Process

The maxillary bone model was created using Cone-Beam Computed Tomography (Planmeca ProMax 3D Mid CBCT, Planmeca, Romexis, Finland, Helsinki) data from an adult patient with no previous craniofacial anomaly from the archives of Ankara Yıldırım Beyazıt University, Faculty of Dentistry, Department of Radiology. Segmentation and STL model formation were performed in 3D Slicer which is freely accessible online software, and the final modeling of the maxillary bone was performed in ANSYS SpaceClaim (Ansys Inc., Canonsburg, PA).

A full-toothed maxillary model without upper third molars was created by adding cortical and trabecular bone, PDL, and gingiva to the maxillary bone model (Figure 1). Two different aligner thicknesses were applied to this model. The aligner trimline ending at the gingival margin was made with an external offset on the model containing all tooth crowns and in a straight shape without following the lace form of the gingiva. The aligner trimline ending 2 mm above the gingival margin was made by extending the trimline by 2 mm. The thickness of the aligners was determined to be 0.5 mm.

The integration of the dental and bone regions was successfully confirmed. After this, the model was standardized, leading to a complete maxillary model that is ready for analysis. All prepared models were accurately placed in 3D space using ANSYS SpaceClaim software, thereby finishing the modeling process.

Making the mesh structure

To create models with 3D solid elements, 4-node tetrahedral elements were utilized in ANSYS Workbench software. On average, a total of 181.267 nodes and 660.470 elements were used.

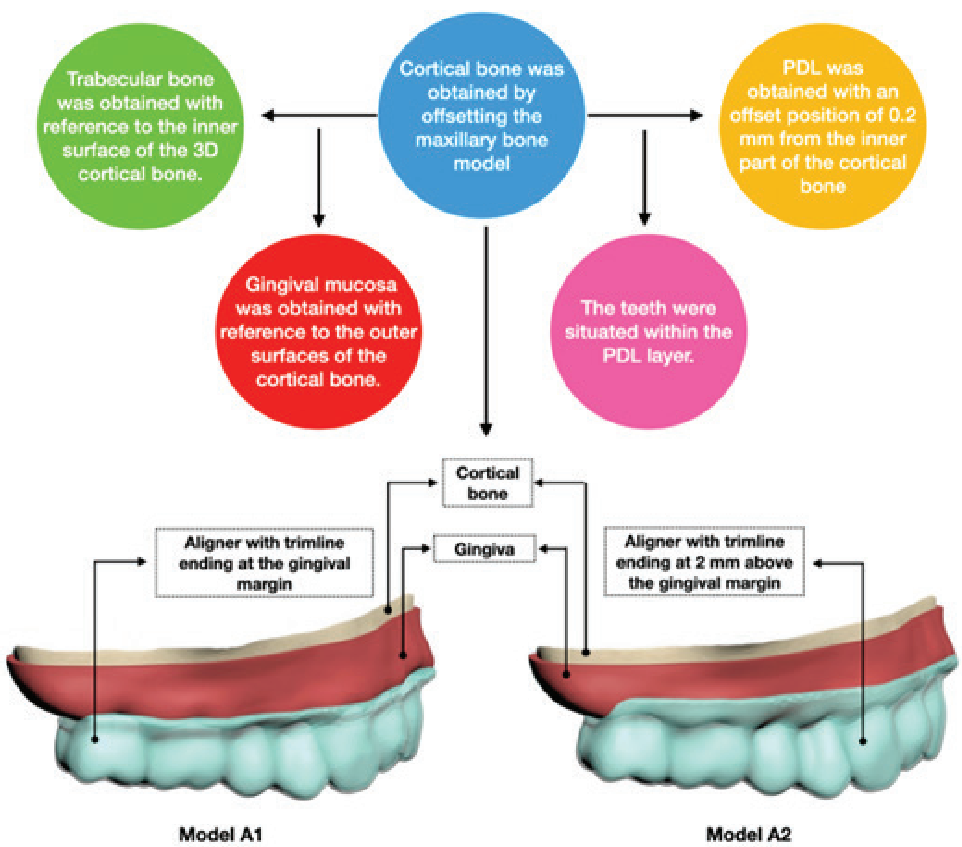

Figure 1. Workflow of 3D model construction

Obtaining Mathematical Models

The mathematical models were created with ANSYS Workbench software and were then transferred to the LS-DYNA (ANSYS Inc., Canonsburg, PA) solver for the analyses.

Defining and Applying Loading Scenarios and Boundary Conditions

Models were fixed at the nodal points in the superior region of the bone by restricting all degrees of freedom to prevent movement in all three axes. A boundary condition was applied to all parts of the model normal to the X-axis and symmetrical on the Y-Z plane. The movements of the molar teeth were buccal (-) and palatinal (+) on the X-axis, mesial (-) and distal (+) on the Y-axis, occlusal (-) and gingival (+) on the Z-axis. The simulated movement was a distalization of 0.25 mm of the upper first and second molar as described in a study by Liu *et al.*[24] Additionally, applying a 0.25 mm displacement —exceeding the modeled PDL thickness of 0.20 mm—allows for a focused assessment of how this specific magnitude of movement affects the biomechanical response of the PDL.The von Mises stress values on the PDL and the second molar tooth and the displacement data of the second molar tooth were analyzed. Points set as reference for displacement data were Meziobuccal Cusp Tip (MBCT), Distobuccal Cusp Tip (DBCT), Meziopalatinal Cusp Tip (MPCT), Distopalatinal Cusp Tip (DPCT), Meziobuccal Root Apex (MBRA), Distobuccal Root Apex (DBRA) and Palatinal Root Apex (PRA).

For all models, a non-linear frictional contact with a coefficient of μ = 0.2 was defined at the aligner-tooth and aligner-attachment interfaces. A bonded contact was defined between the other contacting components.

RESULTS

Stress values

In Model A1, the upper second molar's PDL had a maximum von Mises stress of 0.3268 MPa (Figure 2). High-stress areas were on the buccal side's middle and cervical thirds. Low-stress areas were on the remaining parts, with very low stresses near the palatal root. The tooth's crown had a maximum stress of 32.79 MPa on its mesiobuccal part (Figure 3). The roots had low stresses, especially near the trifurcation region.

In model A2, the upper second molar's PDL had a maximum von Mises stress of 0.3675 MPa (Figure 2). High-stress areas were on the buccal roots' PDL, especially in the middle and apical thirds. Low-stress areas were on the palatinal root and trifurcation region. Maximum von Mises stress on the second molar was 39.18 MPa, and in the crown's occlusal third and mesiobuccal corner (Figure 3). Higher stress areas exist in the trifurcation area and the mesio-buccal enamel-cement junction of the roots. Stress values decrease towards the roots' apical surfaces.

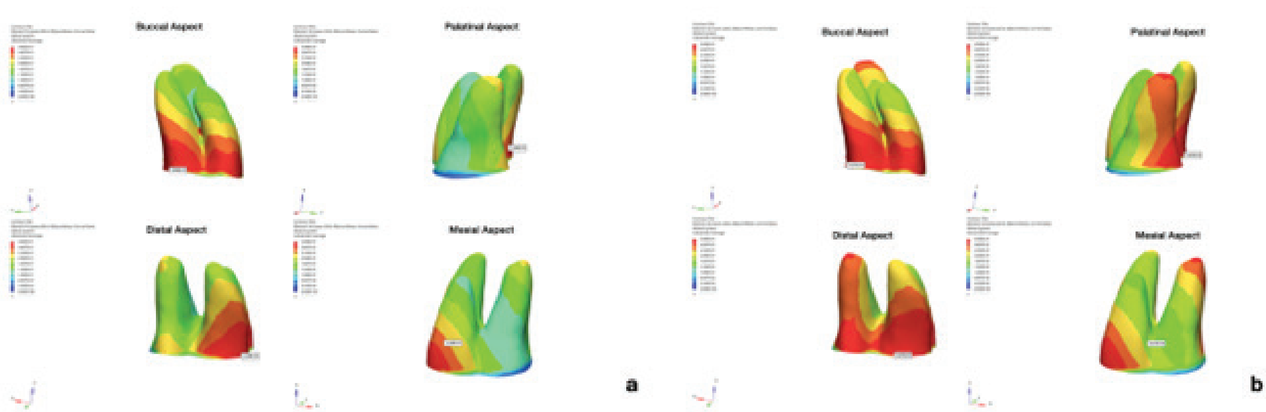

Figure 2. Maximum von Mises stress values and von Mises stress distributions of the PDL of the second molar: a) Model A1; b) Model A2.

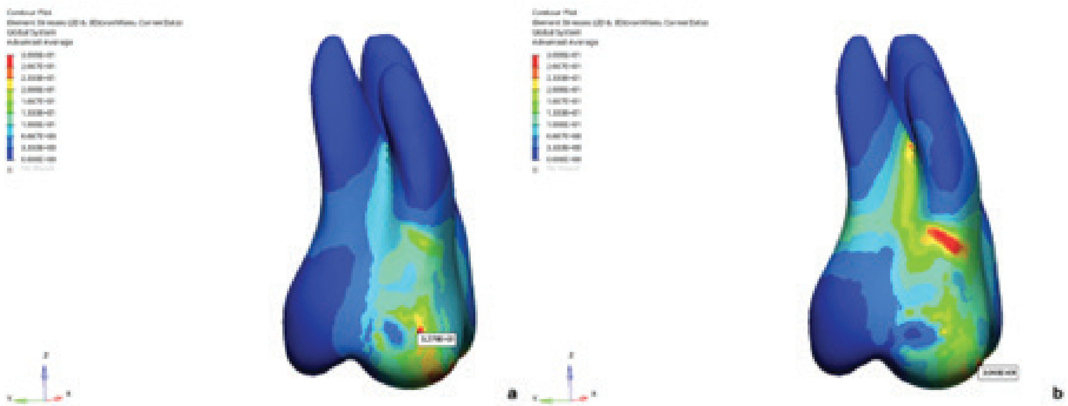

Figure 3. Maximum von Mises stress values and von Mises stress distributions of the second molar: a) Model A1; b) Model A2.

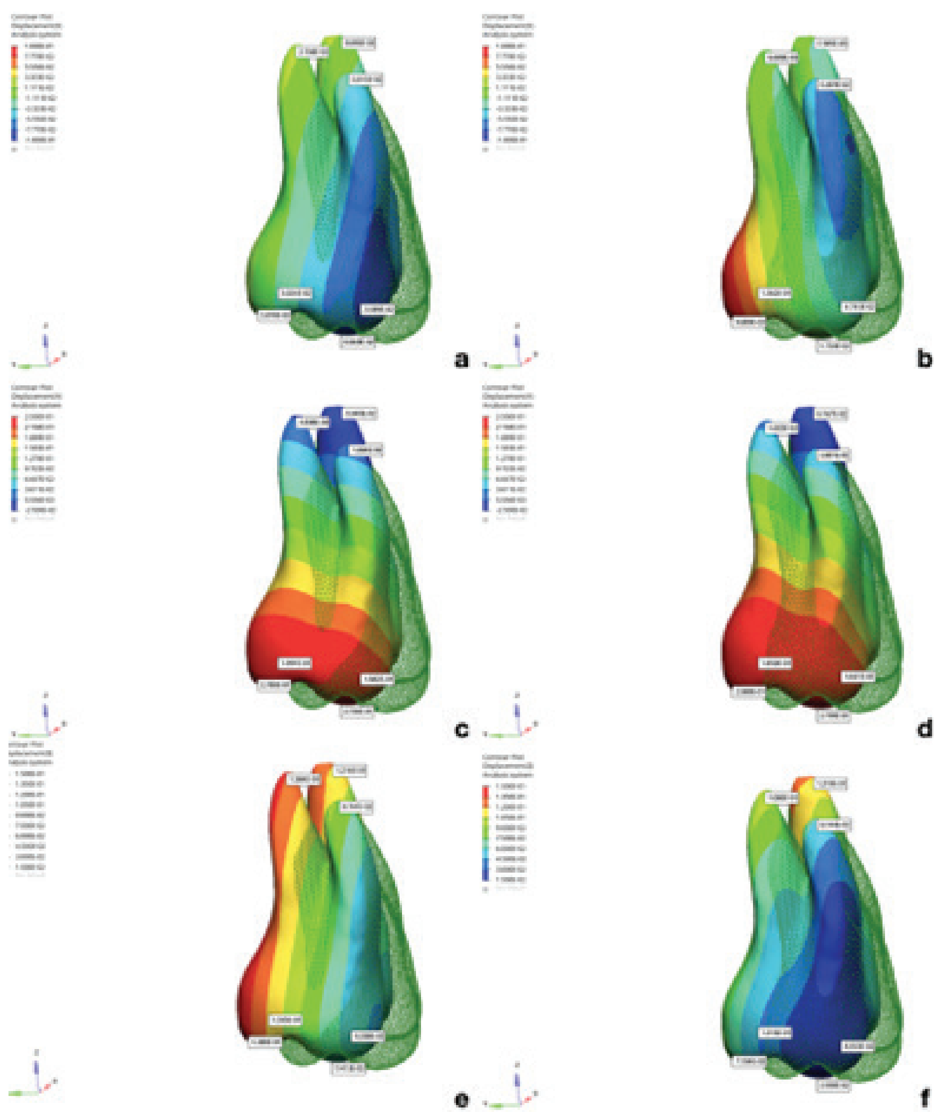

Figure 4. Displacement values of the upper second molar along different axes: (a) X-axis displacement in Model A1, (b) X-axis displacement in Model A2, (c) Y-axis displacement in Model A1, (d) Y-axis displacement in Model A2, (e) Z-axis displacement in Model A1, and (f) Z-axis displacement in Model A2.

Displacements

X-Axis

In Model A1, the X-axis displacement was greatest at MBCT (0.06048 mm) and least at PRA (0.008693 mm), (Figure 4). DBCT, DPCT, DBRA, and PRA moved palatinally, while MBCT, MPCT, and MBRA moved buccally.
In Model A2, the X-axis displacement was greatest at DBCT (0.1362 mm) and least at DBRA (0.006609 mm), (Figure 4). Most points (MBCT, MPCT, DBCT, DPCT, and DBRA) moved palatinally, while MBRA and PRA moved buccally.

Y-Axis

In Model A1, DBCT had the largest displacement (0.2780 mm) in the Y-axis in the distal direction. DBRA had the smallest (-0.001838 mm) in the mesial direction. The other points moved in the distal direction, except for DBRA and PRA (Figure 4).

In Model A2, DBCT had the largest displacement (0.2989 mm) on the Y-axis in the distal direction (Figure 4). DBRA had the smallest (0.01603 mm) again in the distal direction. The other points moved in the distal direction, except for PRA.

Z-Axis

In Model A1, DPCT had the largest displacement (0.1595 mm) in the Z-axis (0.1595 mm) in the gingival direction (Figure 4). MBTT had the least movement (0.07413 mm) in the gingival direction.

In Model A2, DPCT had the largest displacement (0.1316 mm in the Z-axis) in the gingival direction (Figure 4). The least movement in the Z-axis was observed at MBCT (0.0293 mm) in the gingival direction.

DISCUSSION

There is a substantial body of research examining the efficacy of various attachment designs. Although less extensively investigated, studies on aligner designs also feature significantly within the existing literature. [13-15,25] These studies have evaluated the effects of aligner designs across a range of variables, including aligner thickness, trimline length, and form. A limited number of studies have evaluated the efficacy of individual tooth movements, including distalization, intrusion, and torque when performed with aligner designs.[3,10,11,15,19]

FEA is a frequently employed method for digitally investigating the biomechanics of tooth movements in a preclinical context. [11,20,24,26] The capacity to examine both stresses in specific regions and displacement data in modeling enables evaluation from a multitude of perspectives, thereby guiding clinical applications. Furthermore, FEA has been employed in numerous investigations examining the efficacy of distalization using aligners.[18,19,27]

It has been reported that undesirable effects, such as tipping or loss of anchorage, are observed more frequently when distalization is performed without attachments than with attachments. This is particularly the case with aligners of normal trimline length.[19] The importance of attachments in aligner orthodontics is therefore clear. Furthermore, the extension of the trimline to the gingival region is regarded as a crucial aspect. The gingival extensions of the aligner are presumed to facilitate the application of force in a manner that aligns with the resistance center of the tooth, thereby enabling more precise movement.[16]

The aligner with a normal trimline generates stress mostly at the coronal level. The stress decreases and almost disappears as it moves towards the root tips. Studies state that the stress accumulation observed in the PDL and alveolar bone is mostly in the cervical 1/3 region of the tooth and decreases towards the apical parts.[19,24]

In our study, we found that the stresses in the apical part of the PDL increased as the trimline length increased. Therefore, it should be noted that increasing the trimline length may increase stress transmission. The greatest difference in trimline lengths in periodontal areas was seen in the PDL of the palatinal root. Increasing the trimline length increased the von Mises stress in the palatinal root. So significantly that high-pressure areas were observed up to the apical parts of the root. It was observed that a longer trimline may increase stress. It could transmit the applied force more to the roots. This may help to achieve more parallel movement. Studies have also found that increasing the trimline length both increases the force transmission and provides ease of control.[13,14,16] However, this also raises the possibility of resorption in the root areas where there is a high level of force transmission, and this should be carefully monitored on a clinical basis.[28]

Stress areas on the crown increased and moved towards the roots as the trimline lengthened. This suggests that the force transmitted to the roots also increases, which may enhance root movement. Elshazly *et al*.[14] found that straight, elongated trimlines provide more even force transmission and stress distribution.

In both groups, distal rotation of the second molar tooth on the X-axis developed as a result of distal displacement application. A greater degree of distal rotation was observed with the longer trimline. This may be attributed to the fact that the displacement force is applied mesiobuccally, with the force being transmitted more along the length of the trimline, which results in increased rotation. A recent retrospective study revealed significant mesiobuccal rotation and buccal inclination of maxillary molars following 2 mm of distalization using aligners.[29]

In the Y-Axis, longer trimlines led to a greater displacement of the crown and roots in the distal direction. Thus, longer aligners may be more effective in force transmission. Additionally, both models showed displacement of the palatinal root tip in the mesial direction. However, the normal trimline length also led to mesial movement at the disto-buccal root tip. This suggests that distalization of upper second molars without attachments may achieve less tipping when using longer trimlines. A previous study by Ayidaga and Kamiloglu [19] found similar distal tipping in all three models they used. In addition to testing a model without an attachment, they also compared the effectiveness of different attachment designs. In many studies, it has been observed that when maxillary molars are distalized, there is a reciprocal occurrence of distobuccal tipping of the molars and mesiobuccal tipping of the anterior anchor teeth. [26,27]

In the Z-Axis, in the case of longer trimlines, there was a notable reduction in the degree of movement difference observed in the mesial and distal regions of the tooth, in comparison to those with normal trimlines. It was, therefore, determined that the longer trimline exhibited greater control concerning the occlusogingival movements.

Orthodontic tooth movement is influenced by the force vector and the tooth's center of resistance.[29] Aligners with straight, elongated trim lines exert force close to this center, facilitating complex movements such as translation and root movement. Therefore, adjusting aligner designs can enhance root control.[3,30] Additionally, Gao *et al*. [25] reported that the forces produced by the aligner varied depending on aligner width, trimline design, and extension, with non-extended aligners producing significantly lower forces than extended ones. Straight extended trimlines typically show better force delivery and retention, which results in more predictable clinical outcomes. This might reduce the need for revisions. As a result, it can shorten treatment time and improve patient satisfaction.[30]

Upon examination of these findings, it was determined that the extended trimline exhibited superior force transmission and motion biomechanics in upper second molar distalization performed without attachments.

This study used a FEA to examine the movement applied to teeth on artificial models designed virtually. It is therefore possible that the results may not be entirely consistent with those observed in the oral environment. This represents the most significant limitation of the study. Nevertheless, it may serve as a point of reference for future studies and clinical applications. Furthermore, as the process of distalization was initiated with the upper second molar, the motion and stress values of that specific tooth were taken into consideration. Further studies could yield more comprehensive findings on molar distalization by evaluating the response of teeth that will undergo distalization after the second molar or anchorage teeth through a combination of clinical and finite element method studies.

CONCLUSION

Increasing the trimline length of the aligners increased the stress distribution on the teeth and PDL.

As the aligner trimline length increased, the distal movement of the teeth increased.

In upper molar distalization without attachments, a longer aligner trimline will create a more controlled biomechanical effect.

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The authors extend their sincere gratitude to Tinus Technology for its invaluable assistance in simulation and finite element analysis.

Şeffaf Plaklarla Gerçekleştirilen Distalizasyonda Bir Değişken Olarak Trim Hattı Uzunluğu: Sonlu Elemanlar Analizi Çalışması

ÖZET

Amaç: Bu çalışmanın amacı distalizasyon işlemi sırasında şeffaf plaklara ait trimline uzunluğunun üst ikinci molar dişin hareketi üzerindeki etkisini değerlendirmektir.

Gereç ve Yöntem: Farklı şeffaf plak trim hattı uzunlukları kullanılarak iki sonlu eleman modeli geliştirilmiştir. Modellerden birinde dişetinde bir trim hattı bulunurken (Model A1), diğerinde bunun 2 mm üzerinde konumlandırılmış bir trim hattı mevcuttur (Model A2). Her iki plak modeli de üst üçüncü molar dişler hariç olmak üzere üç boyutlu tam dişli bir maksiller modele uygulanmıştır. Dişler üzerine herhangi bir ataşman uygulaması gerçekleştirilmemiştir. Simülasyon sırasında, üst birinci ve ikinci azı dişlerine 0.25 mm'lik bir distal deplasman uygulanmıştır. Diş yer değiştirme verilerinin yanı sıra üst ikinci molar diş ve periodontal ligamenti ile ilişkili von Mises stresine ait sonuçlar analiz edilmiştir.

Bulgular: Periodontal ligamentin (PDL) apikal bölgesindeki stresler daha uzun trim hatları ile artmıştır. Kuron, her iki modelde de esas olarak mezial tarafta stres alanları sergilemiştir. Model A2'de stresler distale doğru yayılmaya başlamış ve köklerdeki stresler de artmıştır. Her iki grup da distopalatal yönde rotasyon sergilemiş ve Model A2 daha büyük bir distal kuron yer değiştirmesi göstermiştir.

Sonuç: Trimline uzunluğunun artırılması, distalizasyon sırasında üst ikinci molar dişlerin hareketini yönetmek için daha etkili bir yaklaşımdır.

Anahtar Kelimler: Biyomekanik; Distalizasyon; Sonlu elemanlar analizi; Şeffaf plak

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