AJO-DO

The mechanical effect of geometric design of attachments in invisible orthodontics

Waheed Ahmad,[a,b] Feifei Jiang,[a] Jing Xiong,[a] and Zeyang Xia[a,c]
Shenzhen and Beijing, China

Introduction: In invisible orthodontics, attachments are used with aligners to better control tooth movement. However, to what extent the geometry of the attachment can affect the biomechanical properties of the aligner is unknown. This study aimed to determine the biomechanical effect of attachment geometry on orthodontic force and moment using 3-dimensional finite element analysis. **Methods:** A 3-dimensional model of mandibular teeth, periodontal ligaments, and the bone complex was employed. Rectangular attachments with systematic size variations were applied to the model with corresponding aligners. Fifteen pairs were created to move the lateral incisor, canine, first premolar, and second molar mesially for 0.15 mm, respectively. The resulting orthodontic forces and moments were analyzed to compare the effect of attachment size. **Results:** Expansion in the attachment size showed a continuous increase in force and moment. Considering the attachment size, the moment increased more than the force, resulting in a slightly higher moment-to-force ratio. Expanding the length, width, or thickness of the rectangular attachment by 0.50 mm increases the force and moment up to 23 cN and 244 cN-mm, respectively. The force direction was closer to the desired movement direction with larger attachment sizes. **Conclusions:** Based on the experimental results, the constructed model successfully simulates the effect of the size of attachments. The larger the size of the attachment, the greater the force and moment, and the better the force direction. The appropriate force and moment for a particular clinical patient can be obtained by choosing the right attachment size. (Am J Orthod Dentofacial Orthop 2023;164:183-93)

Orthodontics is a pivotal branch of dentistry that focuses on diagnosing and treating malocclusions. Two widely accepted orthodontic techniques are usually used to prevent dental illnesses and promote oral health: traditional fixed orthodontics with metal braces and invisible orthodontics with clear aligners.[1] Invisible orthodontics has recently increased in popularity because of the advantages of esthetic, hygienic, and minimally invasive qualities.[2-4] This has inspired biomechanical research to focus on developing clear aligners.[1,5] Invisible orthodontics treatment involves a series of clear aligners with a predetermined mismatch between aligner and crown to move teeth to the desired anatomic position.[6,7] Such predetermined mismatch generates a 3-dimensional force system all over the contact surface, which induces tooth movement.[1,5,8] The design of clear aligners include material, the amount of mismatch, thickness, and integration of the auxiliary devices such as attachment, which are determined by the patient's specific requirements and diagnosis.[9]

Attachment plays a vital role in invisible orthodontics. However, using only aligners may reduce treatment efficacy by causing teeth to move in directions other than those intended by the orthodontists.[10] That is because the force system required to move the teeth is generated by a geometric mismatch between the crowns and clear aligner, then transmitted to a larger, less-defined contact area.[11] Attachments are integrated into the target or neighboring teeth to guarantee the desired force system.[12] The use of attachment enables

[a]Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China.
[b]University of Chinese Academy of Sciences, Beijing, China.
[c]CAS Key Laboratory of Human-Machine Intelligence-Synergy Systems, Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China.
All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest, and none were reported.
This work was supported by the National Natural Science Foundation of China (U2013205), the Chinese Academy of Sciences Youth Innovation Promotion Association Excellent Member Program (Y201968), Guangdong Basic and Applied Basic Research Foundation (2020A1515010651), and Shenzhen Institute of Advanced Technology Innovation Program for Excellent Young Researchers.
Address correspondence to: Zeyang Xia, Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, 1068 Xueyuan Ave, Shenzhen, China 518055; e-mail, zy.xia@siat.ac.cn.
Submitted, June 2022; revised and accepted, November 2022.
0889-5406/$36.00

https://doi.org/10.1016/j.ajodo.2022.11.019

complex tooth movements such as incisor torque, rotation, and molar distalization.[13,14]

The mechanical effect of the attachment geometry is significant because it can potentially influence orthodontic tooth movement by altering the force and moment generated by the aligner.[15,16] A tooth can be moved in response to bone modeling and remodeling with suitable orthodontic force.[17] In contrast, an increased force increases the likelihood of side effects such as external apical root resorption, uncontrolled tipping, and increased hyalinization, all of which are always at the expense of patient comfort and clinical efficiency.[18-20] Theodorou et al[18] recent research on fixed braces indicated that forces of 50-100 cN magnitudes are optimal for orthodontic tooth movement. Luppanapornlarp et al[21] suggested that although forces between 50 cN and 150 cN induce similar and desired tooth movement, higher forces increase pain and abnormal inflammation. There is no comparison of force magnitudes for clear aligners available in clinical or computational studies. Understanding the appropriate attachment geometry for a given clinical scenario can assist orthodontists in obtaining optimal force and moment to prevent potential side effects.

However, the mechanical effect of the attachments' size is still unknown. According to the literature, various attachment types have been tested, each showing a promising effect on orthodontic force.[8,22-25] In certain situations, applying attachments on tooth surfaces has been demonstrated to result in more favorable tooth movements.[11,26,27] A few studies have been undertaken to determine the impact of morphology and positioning of these attachments on tooth movement.[22,27,28] Finite element analysis (FEA) is often recommended as a biomechanical analysis solution for orthodontic treatment because it is an effective way to determine the deformation of solid geometric bodies and the stress distribution on those bodies.[29-32] It provides an accurate and noninvasive technique that estimates the response generated in different tissues[33,34] such as periodontal ligament (PDL), alveolar bone,[35] and teeth.[11] FEA has been performed in literature to analyze stress distribution in alveolar bone, PDL,[24,25,29] forecast tooth displacements,[36-38] optimize aligner design,[17,24] and investigate the need for attachments.[22,26] However, these studies do not emphasize the effect of attachment geometry, which would have required many more model construction and experimentations.

This study aimed to determine how the geometry of an attachment can affect the mechanics of a clear aligner. Hence, we proposed a comprehensive investigation of different sizes of rectangular attachments on 4 teeth of different geometries to evaluate their impact on orthodontic force and moment. We hypothesized that a larger attachment size would result in a higher force system for the intended orthodontic tooth movement while preventing undesired movements.

MATERIAL AND METHODS

A finite element (FE) model of mandibular teeth, PDL, and bone complex were constructed to compare the mechanical effect of attachment size. The basic rectangular attachment (vertical) with different sizes was applied to all teeth with corresponding clear aligners. The initial response of force and moment on the lateral incisor (tooth 1), canine (tooth 2), first premolar (tooth 3), and second molar (tooth 4) were analyzed to estimate the mechanical effect of attachment size.

This study examined the biomechanical effect of altering the dimensions (length, width, and thickness) of rectangular attachments on the properties of invisible orthodontics. Hence, we began with the basic vertical rectangular attachment to demonstrate the mechanical effects of attachment size. To make simulations more realistic, all 14 teeth (except the third molar) were included in the study, and attachments were applied to each tooth to maintain consistency. Simulations were performed on 16 different FE models, each with a unique attachment size and 1 with no attachment to translate teeth 1-4 in the mesial direction.

The effect of attachment size was evaluated by the force system. In each test, the force and moment applied to the target tooth were recorded, the moment-to-force ratio (M/F) was calculated, and the direction of the force and moment was recorded and compared with the desired movement direction.

The FE model was constructed using cone-beam computed tomography scans (using an i-CAT NG scanner [Imaging Sciences International, Hatfield, Pa] with a 120 kV, 5 mA, a matrix of 624 × 624, a resolution of 0.25 mm isotropic voxel, and the time of exposure of 6 seconds) from a single volunteer (healthy male, aged 28 years). Three-dimensional models of rectangular attachments were constructed and bonded to the crown center of the mandibular teeth using Boolean addition ($a + b = c$) in computer-aided design software (Fig 1). To create PDL around the roots, the roots of the teeth in the model (c) were expanded by 0.25 mm uniformly and subtracted using the Boolean subtraction operation (expanded root − $c = d$).[37] To generate an aligner, the crown of the tooth and the bone complex were expanded uniformly to assume the roles of an aligner and gum. Finally, the original teeth crowns were subtracted from the expanded crowns, as was the expanded bone (expanded crowns and bone complex − $c = e$), to construct aligners. The final aligner

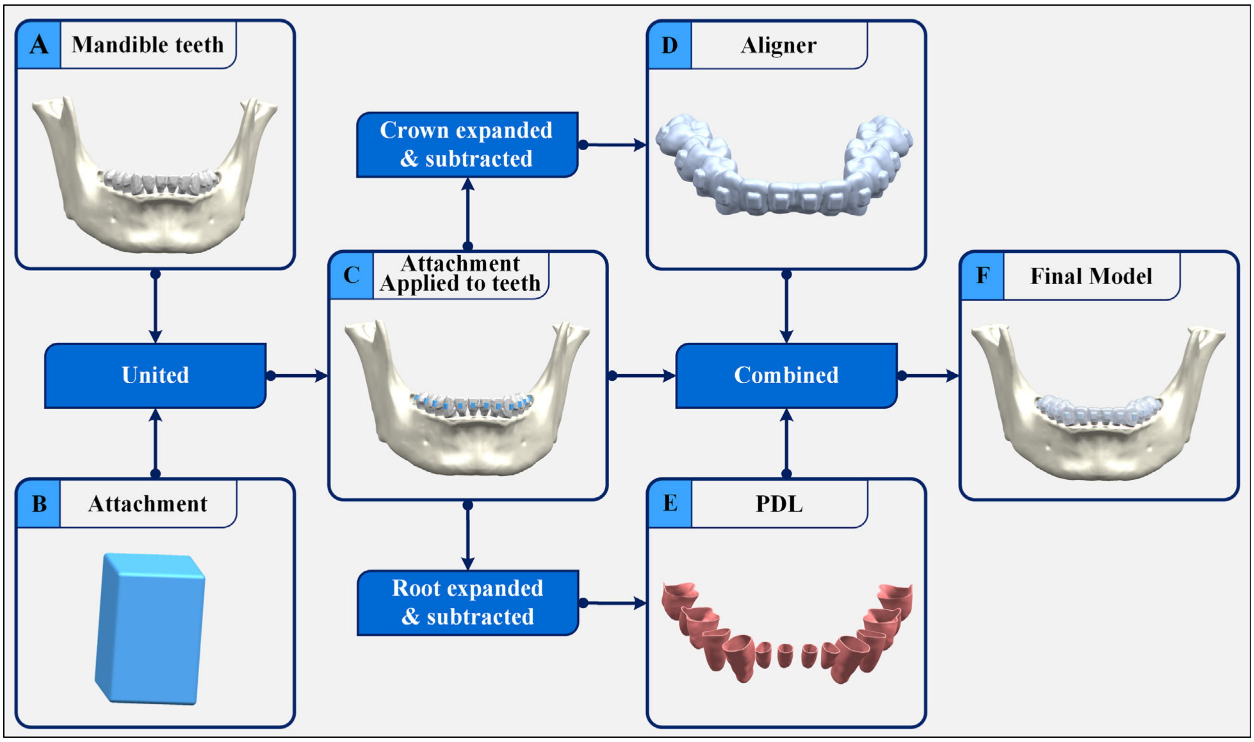


Fig 1. Preparation of aligner model with attachment and its components: **A,** Mandible teeth model; **B,** Rectangular attachment (attachments are added to teeth); **C,** Teeth with attachments are expanded; **D,** Aligner; **E,** PDLs constructed using Boolean subtraction from the expanded model; **F,** Finally, the whole model was combined.

is composed of a uniform thickness of 0.7 mm, with a trimmed surface on the inside same as the teeth crown, whereas the boundaries on the bone complex are just around the gum line. Afterward, the models (c), (d), and (e) were combined to generate the final model (f). The complete FE model includes (a) the bone complex model, (b) teeth with aligner, and (c) attachment configuration (Fig 2). The dimensions of the aligner and attachment are based on the Invisalign system.[13] The basic attachment size was within the range of the Invisalign attachment (length, 3.0-5.0 mm; width, 2.0 mm; thickness, 0.5 mm).[39] To control the complexity of the computation, the material properties of bone, teeth, aligner, and attachment were considered homogeneous, isotropic, and linearly elastic, as widely used in prior work.[29,32,40] The PDL was assumed to be bilinear elastic[32,41] (Table I).

This study was approved by the Institutional Review Board of the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences (approval no. SIAT-IRB-200315-H0477), and written informed consent from the subject was obtained.

In this study, the contact between the aligner and teeth was modeled as frictionless sliding contact because the biological tissue of teeth differs from the material of aligners, and minor movements of the aligner caused by chewing release residual frictional forces.

The load was applied to the target tooth by creating a geometric mismatch between the crown and aligner. The inner geometry of the aligner was aligned with the surface of the teeth crown. In this study, the aligner was configured to induce mesial movement of 0.15 mm on teeth 1-4 (Fig 3). The outer surfaces of PDLs were fixed with alveolar bone. For easy comparison, only 1 tooth was moved in each test. To investigate realistic effects, the entire dental model was used in simulations.

To achieve a smooth loading process, the birth and death method has been used[32] (Figs 3, *A-C*). In the beginning, the aligner and the target tooth overlapped, which represents a mismatch of 0.15 mm between the aligner and the crown of the tooth (Fig 3, *A*). Therefore, we have divided the loading process into 2 steps. The first step is deactivating the aligner-crown contact and displacing it. As a result, the aligner socket perfectly matched the position of the tooth. In the second step, the aligner-crown contact is activated, and the PDL of the target tooth is gradually displaced distally by 0.15 mm. In this manner, the tooth could

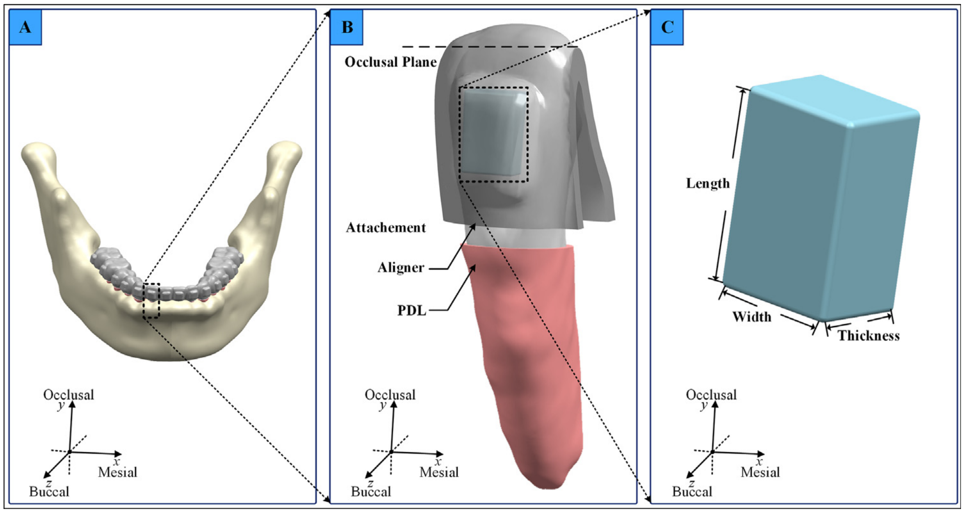


Fig 2. Force loading criteria in invisible orthodontics: **A,** The final FE model; **B,** Force loading on tooth 1 with aligner and attachment; **C,** Attachment size parameters.

Table I. Material properties of the components used in the FEA

Component	*Young's modulus (MPa)*	*Poisson's ratio*
Alveolar bone	345	0.30
Tooth	20,000	0.30
PDL	Bilinear (E_1 = 0.05; E_2 = 0.20; ε_{12} = 7%)	0.30
Plastic aligner	2000	0.40
Attachment	20,000	0.30

return to its original position, and the aligner smoothly loaded the crown (Fig 3, C).

The attachments were divided into 3 groups on the basis of the size parameters (length, width, and thickness). Each group represents only 1 size parameter variation (Table II). In total, 15 FE models with unique attachment sizes with 0.4 mm mesh size were configured, and the results were visualized in FE software. For consistency and easy comparison, all teeth had the exact size of attachments for each test. Thus, 61 trials were executed on the models (15 attachment sizes × 4 teeth) + no-attachment model).

RESULTS

In comparison with all other models with attachment, the results for force, moment, and M/F with the no-attachment model were significantly lower (Figs 4-6).

Attachment size affects the force, moment, and M/F. The magnitude of the force generated by the clear aligner has increased with each expansion in the attachment thickness for teeth 1-4 (Fig 4). The maximum mean force increase because of a 0.5 mm thickness increase of the attachment was 23 cN in tooth 1, whereas the minor change was 10 cN recorded in tooth 4. Similarly, the moment increased with the increase in the thickness of the attachment. The rise in the maximum moment because of a 0.5 mm thickness of the attachment was 230 cN-mm in tooth 1, whereas the smallest change was 102 cN.mm recorded in the molar-thickness relationship with force, moment, and M/F (Table III).

In the case of the width of the attachment, all attributes of the orthodontic force system appear to be influenced similarly by the thickness parameter (Fig 5). The force, moment, and M/F increased with size parameters. The maximum force increased because of a 0.5-mm increase in the width of the attachment, which was 16.51 cN for tooth 1 and 6.03 cN for tooth 4. The maximum moment increase was measured in tooth 1 (171 cN-mm), and the lowest was in tooth 4 (58 cN-mm) for the same size variation (Table III).

The length has also similarly increased force and moment magnitude (Fig 6). In relation to length, the maximum force increase was 17 cN, and the moment was 194 cN-mm for tooth 1, whereas the minimum force increase for tooth 4 was 9 cN, and the moment was 87 cN-mm (Table III).

The M/F slightly increased with attachment size. In Figures 4-6, the *blue* (x) represents the M/F. The rise of the moment because of the thickness increase was slightly higher than the force for all size parameters. Therefore, the resultant M/F increased slightly for all 4 teeth.

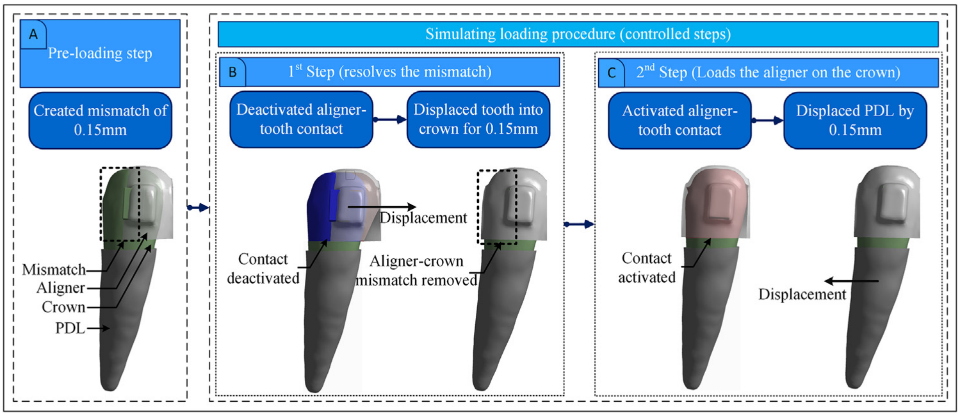


Fig 3. Loading procedure in FEA: **A,** Preloading step; **B,** Simulating loading procedure: first step (resolves mismatch); **C,** Simulating loading procedure: second step (loads the aligner on the crown).

Table II. Attachments geometry based on the length, width, and thickness

Length variations			*Width variations*			*Thickness variations*		
Length	*Width*	*Thickness*	*Length*	*Width*	*Thickness*	*Length*	*Width*	*Thickness*
2.0	2.0	1.0	3.0	1.0	1.0	3.0	2.0	0.5
2.5	2.0	1.0	3.0	1.5	1.0	3.0	2.0	1.0
3.0	2.0	1.0	3.0	2.0	1.0	3.0	2.0	1.5
3.5	2.0	1.0	3.0	2.5	1.0	3.0	2.0	2.0
4.0	2.0	1.0	3.0	3.0	1.0	3.0	2.0	2.5

Note. Values are presented in millimeters.

The size of the attachment affects force and moment magnitude and direction. The magnitude of force and moment has increased in response to the increased attachment size, and the direction has changed toward the intended displacement. The magnitude of force has increased from 103 cN to 135 cN with a 2 mm width expansion (Fig 7). The direction of the force moment has also altered toward the intended displacement. With the same size variation, the total angle has decreased from 4.67° to 0.99° for force and 97.19° to 91.70° for the moment (Table IV). The resultant force was calculated along the mesial direction of each tooth in response to a displacement activation of 0.15 mm. The moment, however, was observed to be somewhat perpendicular to the resultant force.

The von Mises stress distribution on the aligner was examined in this study (Fig 8). In no-attachment models, the buccal edge of the aligner was subjected to highly concentrated stress of 12.67 MPa. The stress values for size parameters seem to decrease with each increase in attachment thickness. Nevertheless, the stress for length and width of attachment decreased for 2 mm of size increase but increased afterward.

DISCUSSION

In invisible orthodontics, understanding the biomechanical impact of an attachment's geometry is crucial and indispensable. In this study, we investigated the length, width, and thickness parameters of attachments from a comprehensive biomechanical perspective. The same trend in the results was obtained by repeating and validating the experiments with different teeth, which could serve as a guide for orthodontic practitioners.

One of the critical attributes of the obtained results from the FE simulations is that all forces, moments, and M/Fs are within the acceptable range. Several FE studies have been conducted recently to determine the induced force values during orthodontic treatment. Savignano et al[36] employed various attachment techniques and obtained tooth 1 extrusion force values of 200 cN. Gomez et al[26] achieved distal movement of tooth 2 using 286 cN force using a composite attachment. Yokoi et al[29] used 330 cN of force during tooth 1 mesiodistal movement. A FE study by Goto et al[22] achieved forces up to 2600 cN to distally retract tooth 2. Other studies have applied force directly in clear aligner treatment to

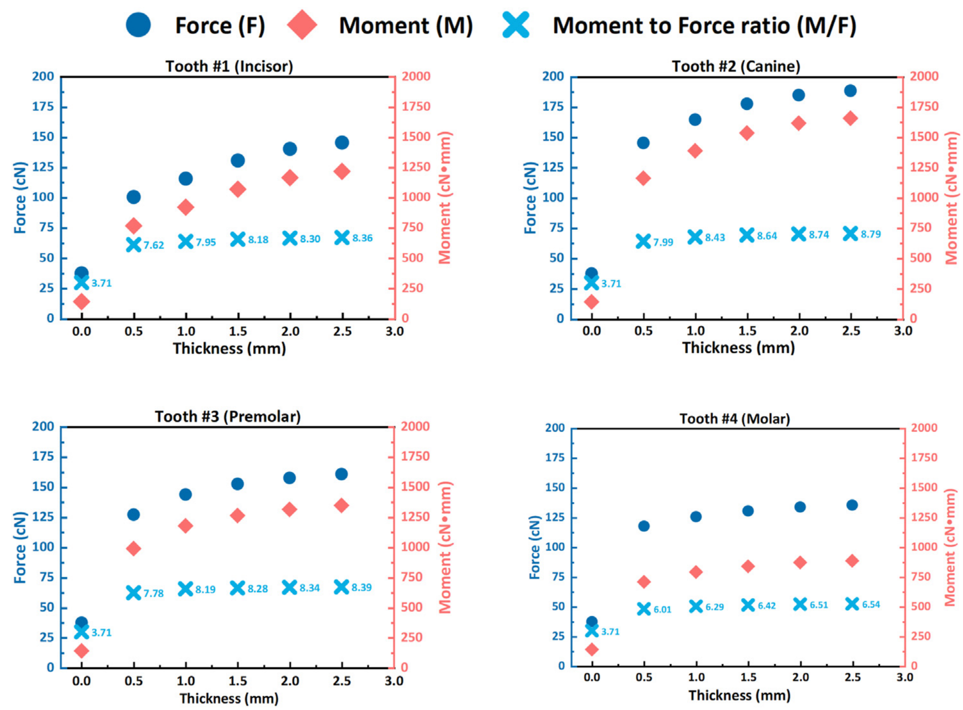


Fig 4. Relationship of the attachment's thickness (0.0 represents no-attachment model) with force, moment, and M/F for the intended displacement in tooth 1 (incisor), 2 (canine), 3 (premolar), and 4 (molar).

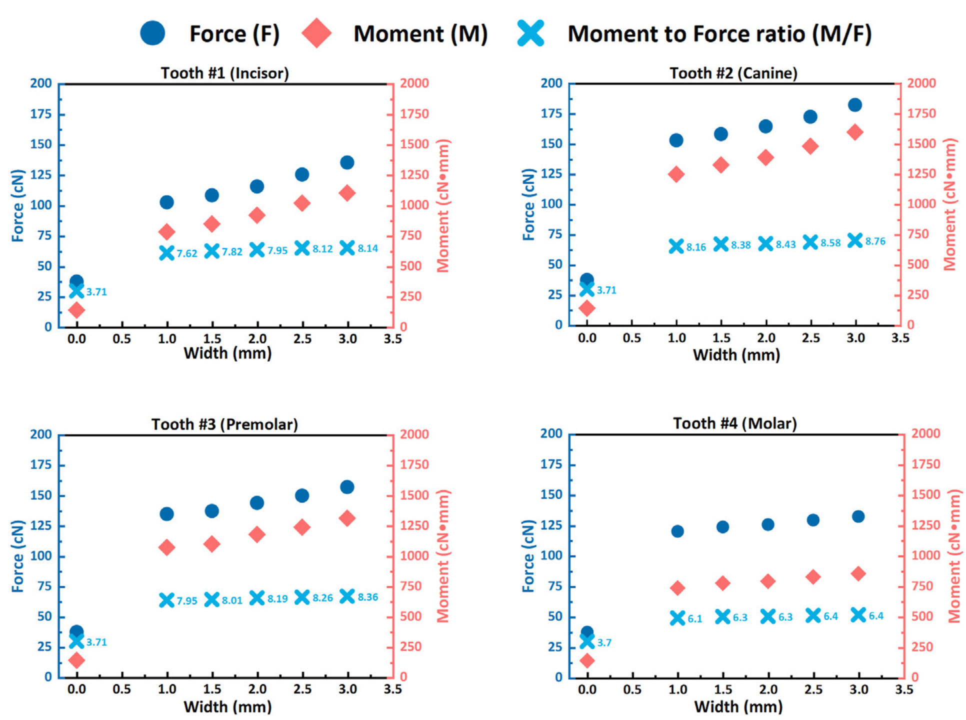


Fig 5. Relationship of the attachment's width (0.0 represents no-attachment model) with force, moment, and M/F for the intended displacement in tooth 1 (incisor), 2 (canine), 3 (premolar), and 4 (molar).

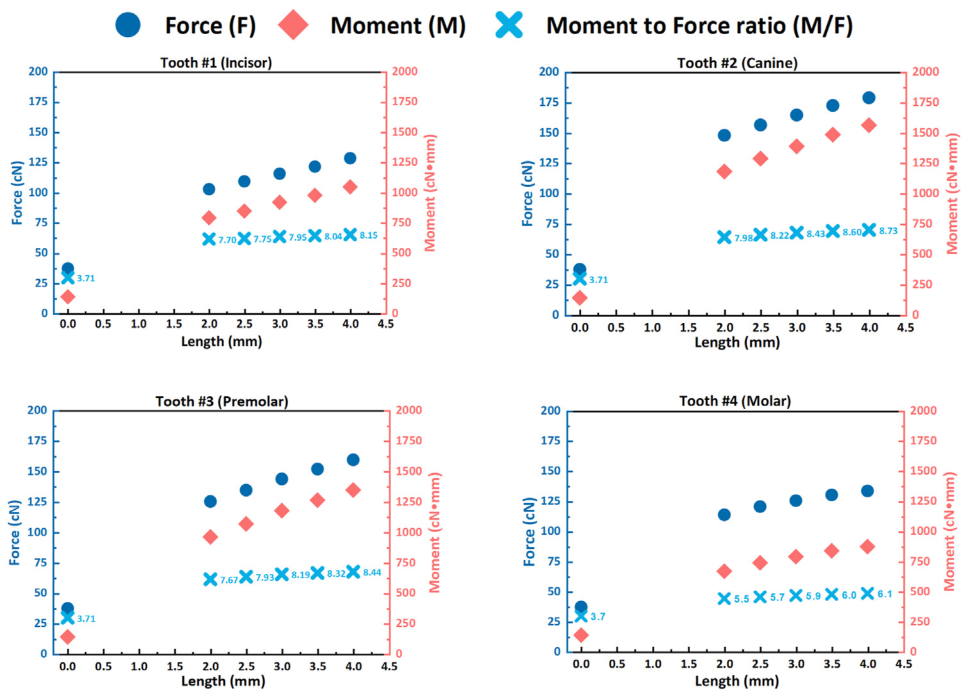


Fig 6. Relationship of the attachment's length (0.0 represents no-attachment model) with force, moment, and M/F for the intended displacement in tooth 1 (incisor), 2 (canine), 3 (premolar), and 4 (molar).

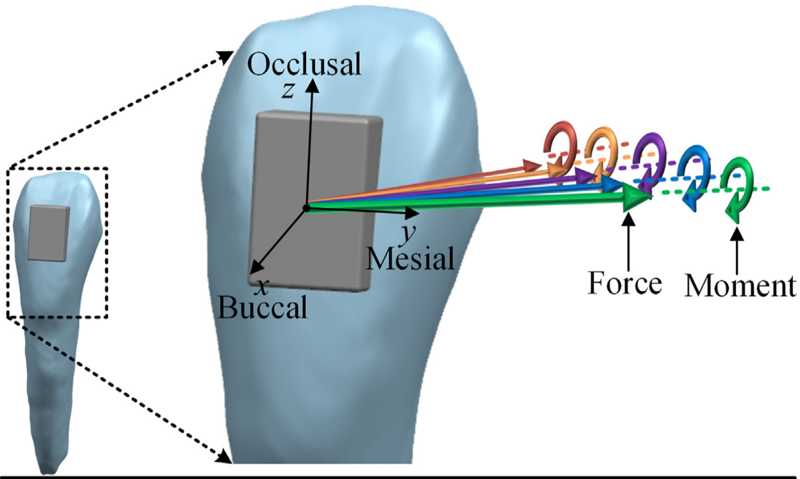
Table III. The increase in the values of force and moment because of 0.5 mm size expansion

Tooth no.	*Force (cN)*	*Moment (cN.mm)*
Thickness		
1	23	244
2	21	230
3	16	171
4	10	102
Width		
1	17	171
2	15	162
3	12	124
4	06	058
Length		
1	17	194
2	16	192
3	13	128
4	09	087

the tooth surface to achieve desired tooth movement.[28,42,43] However, the forces we measured in our study were from 50 cN to 190 cN.

Another important finding of this study is that all size parameters showed a similar trend for force, moment, and M/F. The attachment size has increased force and moment (Figs 4-6). The no-attachment model has a significantly lower force system than the attachment model. The increase in force and moment for a 0.5 mm size variation of attachment also shows a notable trend (Table III). The highest force and moment values were recorded for tooth 1, whereas the lowest values were observed for tooth 4. In addition, the thickness parameter has a larger effect on the force and moment than length and width. For all models, the increase in moment values was higher than the force, which resulted in a slight rise in the M/F. The attachment size only has a mild effect on M/F. In accordance with the results of the FEA, the attachment size is considered important in controlling the force and moment. It was observed that the force and moment of tooth 2 (and to a minor extent also for tooth 3) do not significantly change after reaching a threshold point. However, in aligner treatment, force generation is a complex process. Although the force in this study was primarily determined by the attachment size, it is also influenced by geometry and adjacent teeth. It is possible that the force vs size curve was not linear and cannot exceed a certain upper limit. Thus, it was the main reason for the FE study to investigate the problem.

The Von Mises stress distribution on aligners in relation to attachment size has also been studied (Fig 8). In the no-attachment model, stress values are



Attachment Size	Force		Moment	
	Magnitude	Direction	Magnitude	Direction
1.0mm	103cN	4.67°	728cN.mm	97.19°
1.5mm	108cN	4.12°	748cN.mm	96.35°
2.0mm	116cN	3.11°	920cN.mm	94.85°
2.5mm	126cN	2.05°	1019cN.mm	93.18°
3.0mm	135cN	0.99°	1103cN.mm	91.70°

Fig 7. Increased attachment size alters the force and moment toward the intended displacement direction.

comparatively more concentrated on the lower edge of the aligner on tooth 1. However, they are more evenly distributed around the attachment area on the aligner with the attachment models. A continuous decrease in stress has been observed for the thickness parameter because of increased attachment size. However, there were inconsistent results in the stress values for width and length variations in attachments, in which, after a threshold, an increase in attachment size increases the stress on the aligner. A possible explanation could be that variations in attachment size affect the aligner's morphology as well.

In addition, attachment designs (size parameters) can be adjusted to generate appropriate orthodontic force. A recent quantitative study demonstrated that 50 cN to 250 cN of force could produce similar orthodontic tooth movement without the adverse effects of excessive inflammation, pain, or hyalinization.[18] Based on our results regarding attachment size, it is possible to provide recommended attachment sizes because the force system required to achieve the required displacement varies with attachment size. However, it should be noted that because each tooth has a unique morphology, the magnitude of the force system required to achieve the desired tooth movement is also different. In this regard, the recommended attachments for each tooth will differ; for example, the attachment size for tooth 1 should be 1.0-4.0 mm in length, 1.0-2.5 mm in width, and 0.5-1.0 mm in thickness. For tooth 2, the size should not exceed 2.0 mm in length, 1.0 mm in width, and 0.5 mm in thickness. For tooth 3, it should be 1.0-3.0 mm in length, 1.0-2.5 mm in width, and 0.5-1.5 mm in thickness, and tooth 4 should be 1.0-4.0 mm in length, 1.0-2.5 mm in width, and 0.5-1.0 mm in thickness. In addition, the default size of a rectangular attachment in Invisalign is 3-5 mm in length, 2 mm in width, and 0.5-1.0 mm in thickness.[39] In this way, the esthetic property can also be maintained while delivering an optimal force system.

Furthermore, the size of the attachment affects force and moment magnitude and direction. A change in magnitude and direction of force and moment because of a variation in attachment size is evident (Fig 7). The force and moment direction improved as the attachment size increased (Table IV). The force and moment magnitude has risen with each increase in the width of the attachment, and the angle has also been proven to move toward the intended displacement direction.

Table IV. Relationship of force and moment direction with the attachment size

	Direction			*Direction*			*Direction*	
Thickness	*Force*	*Moment*	*Width*	*Force*	*Moment*	*Length*	*Force*	*Moment*
0.5	4.04°	96.94°	1.00	4.67°	97.19°	2.0	5.06°	97.69°
1.0	3.11°	94.85°	1.50	4.12°	96.35°	2.5	3.80°	95.95°
1.5	1.00°	91.68°	2.00	3.11°	94.85°	3.0	3.11°	94.85°
2.0	0.97°	89.54°	2.50	2.05°	93.18°	3.5	2.55°	94.06°
2.5	0.67°	88.30°	3.00	0.99°	91.70°	4.0	1.89°	93.12°

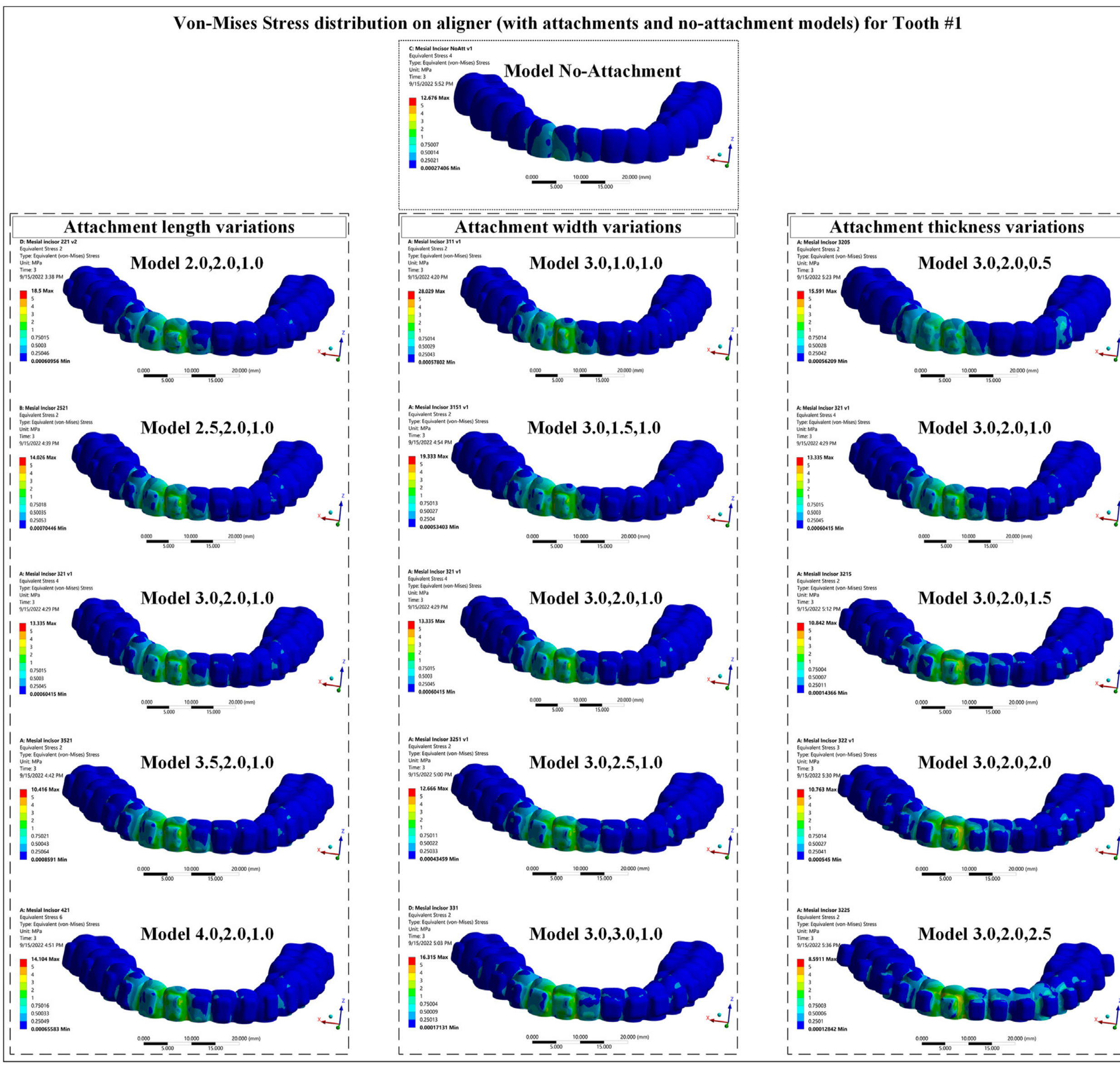


Fig 8. Relationship of von Mises stress with attachment size (tooth no. 1).

In conclusion, this study proposed a comprehensive and clinically applicable investigation of the biomechanical effect of attachment size in invisible orthodontics. The results have been extensively validated on multiple teeth. Dental practitioners can use these results in a clinical case study to provide a precise force value during treatment.

FE offers one of the most effective ways to model contact conditions among anatomic models such as teeth, bones, attachments, and aligners. However, clinical situations may differ. Therefore, in vivo and in vitro studies are necessary to validate FE-driven results.

CONCLUSIONS

This study aimed to determine the biomechanical effects of altering the geometry (length, width, and thickness) of rectangular attachments on the properties of invisible orthodontics using FEA. Taking the obtained results into consideration, the following conclusions can be drawn:

1. The force and moment increased with the thickness, length, and width of attachment sizes.
2. The attachment size only had a mild effect on M/F.
3. The direction of force was better aligned with the desired movement direction with a larger attachment size.
4. The appropriate force magnitude can be obtained by selecting the appropriate attachment size.

AUTHOR CREDIT STATEMENT

Waheed Ahmad contributed to resources, validation, software, conceptualization, methodology, data curation, original draft preparation, visualization, and investigation; FeiFei Jiang contributed to formal analysis, manuscript review and editing, and software; Jing Xiong contributed to formal analysis, manuscript review and editing, and supervision; and Zeyang Xia contributed to conceptualization, formal analysis, manuscript review and editing, visualization, funding acquisition, and supervision.

REFERENCES

1. Littlewood SJ, Mitchell L. An introduction to orthodontics. Oxford: Oxford university press; 2019.
2. Cassetta M, Altieri F, Pandolfi S, Giansanti M. The combined use of computer-guided, minimally invasive, flapless corticotomy and clear aligners as a novel approach to moderate crowding: a case report. Korean J Orthod 2017;47:130-41.
3. Ferlias N, Ostapiuk MA, Diekema TN, Kristensen MG, Kristensen KD, Stoustrup P. Online information on orthodontic treatment in Denmark: a population-based quality assessment. AJO-DO Clinical Companion 2021;1:119-26.
4. Weinstein T, Marano G, Aulakh R. Five-to-five clear aligner therapy: predictable orthodontic movement for general dentist to achieve minimally invasive dentistry. BMC Oral Health 2021;21:671.
5. Proffit WR, Fields HW, Larson B, Sarver DM. Contemporary orthodontics-e-book. Amsterdam: Elsevier Health Sciences; 2018.
6. Han JY. A comparative study of combined periodontal and orthodontic treatment with fixed appliances and clear aligners in patients with periodontitis. J Periodontal Implant Sci 2015;45:193-204.
7. Buschang PH, Shaw SG, Ross M, Crosby D, Campbell PM. Comparative time efficiency of aligner therapy and conventional edgewise braces. Angle Orthod 2014;84:391-6.
8. Ma Y, Li S. The optimal orthodontic displacement of clear aligner for mild, moderate and severe periodontal conditions: an in vitro study in a periodontally compromised individual using the finite element model. BMC Oral Health 2021;21:109.
9. Kohda N, Iijima M, Muguruma T, Brantley WA, Ahluwalia KS, Mizoguchi I. Effects of mechanical properties of thermoplastic materials on the initial force of thermoplastic appliances. Angle Orthod 2013;83:476-83.
10. Ho CT, Huang YT, Chao CW, Huang TH, Kao CT. Effects of different aligner materials and attachments on orthodontic behavior. J Dent Sci 2021;16:1001-9.
11. Barone S, Paoli A, Razionale AV, Savignano R. Computational design and engineering of polymeric orthodontic aligners. Int J Numer Method Biomed Eng 2017;33:e2839.
12. Pan S, Zou D, Pan X, Tsai T-Y. Effect of attachment on movement control of the central incisor using invisible orthodontics: in-silico finite element analysis. J Shanghai Jiaotong Univ (Sci) 2021;26:383-90.
13. Simon M, Keilig L, Schwarze J, Jung BA, Bourauel C. Forces and moments generated by removable thermoplastic aligners: incisor torque, premolar derotation, and molar distalization. Am J Orthod Dentofacial Orthop 2014;145:728-36.
14. Weckmann J, Scharf S, Graf I, Schwarze J, Keilig L, Bourauel C, et al. Influence of attachment bonding protocol on precision of the attachment in aligner treatments. J Orofac Orthop 2020;81:30-40.
15. Weir T. Clear aligners in orthodontic treatment. Aust Dent J 2017;62(Suppl 1):58-62.
16. Ferlias N, Dalstra M, Cornelis MA, Cattaneo PM. In vitro comparison of different Invisalign® and 3Shape® attachment shapes to control premolar rotation. Front Bioeng Biotechnol 2022;10:840622.
17. Henneman S, Von den Hoff JW, Maltha JC. Mechanobiology of tooth movement. Eur J Orthod 2008;30:299-306.
18. Theodorou CI, Kuijpers-Jagtman AM, Bronkhorst EM, Wagener FADTG. Optimal force magnitude for bodily orthodontic tooth movement with fixed appliances: a systematic review. Am J Orthod Dentofacial Orthop 2019;156:582-92.
19. Paetyangkul A, Türk T, Elekdağ-Türk S, Jones AS, Petocz P, Darendeliler MA. Physical properties of root cementum: part 14. The amount of root resorption after force application for 12 weeks on maxillary and mandibular premolars: a microcomputed-tomography study. Am J Orthod Dentofacial Orthop 2009;136:492.e1-9; discussion 492-3.
20. Ferguson DJ, Wilcko MT. Tooth movement mechanobiology. Clin Dent Rev 2018;2:2.
21. Luppanapornlarp S, Kajii TS, Surarit R, Iida J. Interleukin-1β levels, pain intensity, and tooth movement using two different magnitudes of continuous orthodontic force. Eur J Orthod 2010;32:596-601.
22. Goto M, Yanagisawa W, Kimura H, Inou N, Maki K. A method for evaluation of the effects of attachments in aligner-type

orthodontic appliance: three-dimensional finite element analysis. Orthod Waves 2017;76:207-14.
23. Cortona A, Rossini G, Parrini S, Deregibus A, Castroflorio T. Clear aligner orthodontic therapy of rotated mandibular round-shaped teeth: a finite element study. Angle Orthod 2020;90:247-54.
24. Rossini G, Modica S, Parrini S, Deregibus A, Castroflorio T. Incisors extrusion with clear aligners technique: a finite element analysis study. Appl Sci 2021;11:1167.
25. Jiang T, Wu RY, Wang JK, Wang HH, Tang GH. Clear aligners for maxillary anterior en masse retraction: a 3D finite element study. Sci Rep 2020;10:10156.
26. Gomez JP, Peña FM, Martínez V, Giraldo DC, Cardona CI. Initial force systems during bodily tooth movement with plastic aligners and composite attachments: a three-dimensional finite element analysis. Angle Orthod 2015;85:454-60.
27. Rossini G, Parrini S, Castroflorio T, Deregibus A, Debernardi CL. Efficacy of clear aligners in controlling orthodontic tooth movement: a systematic review. Angle Orthod 2015;85:881-9.
28. Kim WH, Hong K, Lim D, Lee JH, Jung YJ, Kim B. Optimal position of attachment for removable thermoplastic aligner on the lower canine using finite element analysis. Materials (Basel) 2020;13:3369.
29. Yokoi Y, Arai A, Kawamura J, Uozumi T, Usui Y, Okafuji N. Effects of attachment of plastic aligner in closing of diastema of maxillary dentition by finite element method. J Healthc Eng 2019; 2019:1075097.
30. Soares CJ, Soares PV, Santos-Filho PC, Armstrong SR. Microtensile specimen attachment and shape–finite element analysis. J Dent Res 2008;87:89-93.
31. Xia Z, Chen J, Jiangc F, Li S, Viecilli RF, Liu SY. Load system of segmental T-loops for canine retraction. Am J Orthod Dentofacial Orthop 2013;144:548-56.
32. Zhou X, Gan Y, Zhao Q, Xiong J, Xia Z. Simulation of orthodontic force of archwire applied to full dentition using virtual bracket displacement method. Int J Numer Method Biomed Eng 2019; 35:e3189.
33. Brunet J, Pierrat B, Badel P. A parametric study on factors influencing the onset and propagation of aortic dissection using the extended finite element method. IEEE Trans Biomed Eng 2021; 68:2918-29.
34. Wang L, Wu Y, Perez KC, Hyman S, Brunski JB, Tulu U, et al. Effects of condensation on peri-implant bone density and remodeling. J Dent Res 2017;96:413-20.
35. Jang AT, Chen L, Shimotake AR, Landis W, Altoe V, Aloni S, et al. A force on the crown and tug of war in the periodontal complex. J Dent Res 2018;97:241-50.
36. Savignano R, Valentino R, Razionale AV, Michelotti A, Barone S, D'Antò V. Biomechanical effects of different auxiliary-aligner designs for the extrusion of an upper central incisor: a finite element analysis. J Healthc Eng 2019;2019:9687127.
37. Xia Z, Jiang F, Chen J. Estimation of periodontal ligament's equivalent mechanical parameters for finite element modeling. Am J Orthod Dentofacial Orthop 2013;143:486-91.
38. Cattaneo PM, Dalstra M, Melsen B. The finite element method: a tool to study orthodontic tooth movement. J Dent Res 2005;84:428-33.
39. Dasy H, Dasy A, Asatrian G, Rózsa N, Lee HF, Kwak JH. Effects of variable attachment shapes and aligner material on aligner retention. Angle Orthod 2015;85:934-40.
40. Gan Y, Xia Z, Xiong J, Li G, Zhao Q. Tooth and alveolar bone segmentation from dental computed tomography images. IEEE J Biomed Health Inform 2018;22:196-204.
41. Papageorgiou SN, Keilig L, Hasan I, Jäger A, Bourauel C. Effect of material variation on the biomechanical behaviour of orthodontic fixed appliances: a finite element analysis. Eur J Orthod 2016;38:300-7.
42. Comba B, Parrini S, Rossini G, Castroflorio T, Deregibus A. A three-dimensional finite element analysis of upper-canine distalization with clear aligners, composite attachments, and Class II elastics. J Clin Orthod 2017;51:24-8.
43. Hahn W, Zapf A, Dathe H, Fialka-Fricke J, Fricke-Zech S, Gruber R, et al. Torquing an upper central incisor with aligners–acting forces and biomechanical principles. Eur J Orthod 2010;32:607-13.