Original Article

Force changes associated with different intrusion strategies for deep-bite correction by clear aligners

Yang Liu[a]; Wei Hu[b]

ABSTRACT

Objectives: To investigate the relationships among different intrusion patterns of clear overlay aligners and the corresponding orthodontic forces and to provide guidance for clinical treatment.

Materials and Methods: Five sets of removable thermoplastic-formed aligners with the same thickness, designed for different intrusion procedures (G0 aligners as a control group, with no activation; G1 aligners for intruding canines; G2 aligners for intruding incisors; G3 aligners for intruding canines and incisors with the same activations; G4 aligners for intruding canines and incisors with different activation), were manufactured, and the corresponding intrusion forces were measured with a multiaxis force/torque transducer measurement system in real time.

Results: With the same activation (0.2-mm intrusion) and rectangular attachments placed on the premolars and first molars, the canines experienced the largest intrusive force when intruded alone using G1 aligners. The canines received a larger intrusive force than incisors in G3. The incisors received similar forces in G2 and G3. First premolars endured the largest extrusive forces when all anterior teeth were intruded with G3 aligners. Extrusion forces were exerted on canines and lateral incisors when using G4 aligners.

Conclusions: Aligners with different intrusion patterns exert different forces on incisors, canines, and premolars, and the forces were closely related to the designed activation, shape and position of the attachment and relative movement of the adjacent teeth. (*Angle Orthod.* 2018;88:771–778.)

KEY WORDS: Aligners; Intrusion; Orthodontic force; Orthodontic treatment

INTRODUCTION

Since Kesling[1] introduced the tooth positioner in 1946, the clear aligner technique (CAT) has been developed further by numerous orthodontists and was formally introduced with the Food and Drug Administration approval of orthodontic use of Invisalign in 1998.[2] With further advances, such as three-dimensional (3D) reconstruction and computer-aided design and computer-aided manufacturing, the invisible orthodontic aligner technique has become a common addition to the orthodontic armamentarium. The CAT is increasing in popularity given its advantages over conventional fixed appliances in terms of esthetics, oral hygiene, comfort for patients, shortened treatment duration, and chair time in mild to moderate cases, despite the higher costs and the unpredictable outcome in certain cases.[3–6]

Numerous studies have investigated the accuracy and efficiency of this technology. Kravitz et al.[7] studied 37 nonextraction patients and found that the mean accuracy of tooth movement with Invisalign was only 41%. Grünheid et al.[8] superimposed posttreatment digital models on corresponding virtual treatment predictions in 30 nonextraction patients who underwent Invisalign treatment and found that maxillary expansion, rotation, and molar torque may not be fully achieved with this approach. Deep-bite correction remains a difficult task for orthodontists when using CAT. Sheridan[9] reported that 70%–80% of CAT cases require further refinement or a combination of fixed appliances.

Although many studies have researched treatment outcomes,[3,5,10,11] the biomechanical mechanisms by

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which CAT exerts its effects remain unknown, and it is challenging to assess the force imparted by these clear aligners. Finite element analysis has been used to provide quantitative and detailed data simulating the physiological tissue reactions during treatment,[12] but finite element analysis results depend directly on the input data, the accuracy of the model, and the boundary conditions and solution, while the accepted physical property values of the supporting tissues still include many discrepancies.

Fast-developing transducer technology has made it possible to measure orthodontic force instantly. The micro-stress sensor system can measure the force delivery properties of aligners with different thicknesses and different activations.[13–15] However, there have been relatively few convincing investigations on the exact biomechanics involved in vertical tooth movements with overlay aligners. If the force system is understood, more predictable tooth movement can be achieved to improve the efficiency and accuracy of invisible orthodontic therapy.

In this study, five sets of removable thermoplastic aligners with the same thickness, designed for different intrusion procedures, were manufactured, and the corresponding intrusion forces were measured with a multiaxis force/torque transducer measurement system in real time. The study sought to investigate the relationships among different intrusion patterns of these aligners and the corresponding orthodontic forces.

MATERIALS AND METHODS

Clear Aligner Design and Fabrication

OrthoDS_D software version 4.4 (Wuxi Angel Align Biotechnology Co Ltd, Wuxi, China) was used to design aligners with different intrusion strategies and different amounts of activation (Table 1) on the standard model (NISSIN P12P-SB1). Each group consisted of 11 aligners. Group 0 (G0) aligners, a control group, produced no activation. Group 1 (G1) intruded both mandibular canines by 0.2 mm. Group 2 (G2) intruded the four mandibular incisors by 0.2 mm. Group 3 (G3) intruded all mandibular anterior teeth (canines and incisors) concurrently, with an activation of 0.2 mm. Group 4 was designed to intrude the canines, lateral incisors, and central incisors with different amounts of activation (by 0.1 mm, 0.15 mm and 0.2 mm respectively). Conventional transverse rectangular attachments were bonded on the mandibular first premolars, second premolars, and first molars.

The aligners were produced using the same process as for customized orthodontic removable thermoplastic appliances.[16] Photosensitive resin models were printed using a 3D printer (Objet30 Pro, Objet Ltd, Rehovot, Israel) according to the digital models. A thermoforming machine was used to manufacture the corresponding thermoplastic aligners with 0.8-mm-thick thermoplastic material (Duran, Scheu Dental GmbH, Iserlohn, Germany). All 55 aligners were then trimmed and numbered (Figure 1).

Table 1. Designed Anterior Teeth Intrusion Test Program of Standard Dentition Model

Amount of Intrusion, mm	33 and 43	32 and 42	31 and 41	Sample Size
G0	0	0	0	11
G1	0.2	0	0	11
G2	0	0.2	0.2	11
G3	0.2	0.2	0.2	11
G4	0.1	0.15	0.2	11

Test Apparatus

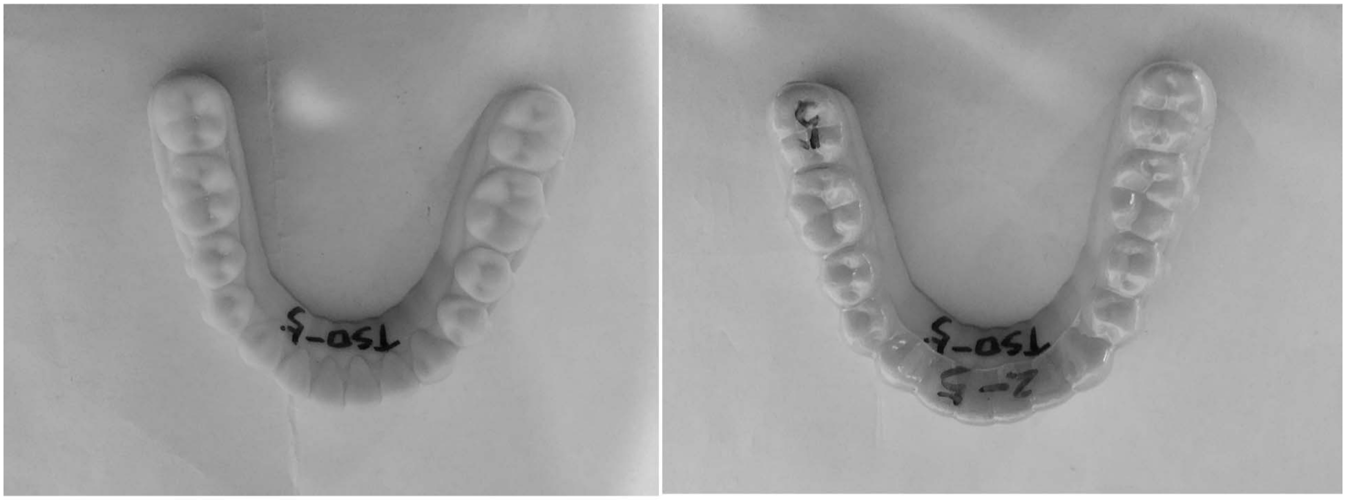
The aligner test setup consisted of 14 three-dimensional force/moment (F/M) sensors (IFPSMC3/4 ATI Industrial Automation, Apex, NC, USA) and 14 isolated 3D-printed resin mandibular teeth (Object 30 OrthoDesk, Stratasys Ltd, Eden Prairie, MN, USA). Each resin tooth was separately mounted on the micro-sensor using three fixed screws (Figure 2).

Monitoring and Analysis of Orthodontic Force in the Vertical Direction

Mechanical calibration was first performed. All measured F/M values were transferred to the estimated center of resistance of each tooth. The G0 aligners were first loaded, and four groups of aligners were successively placed on the F/M measuring system. Forces of G0 aligners (Figure 3) in the vertical direction (*z*-axis) mainly resulted from two errors: one was the error of 3D printing of resin teeth and the other was installation error. After subtracting G0 forces, the vertical orthodontic forces generated by G1–G4 aligners were documented (Figure 4) and mean forces were calculated (Figure 5) and analyzed with SPSS Statistics version 20.0 (SPSS Inc, Chicago, IL, USA). One-way analysis of variance, followed by Bonferroni's test and Dunnett's T3, were performed to detect statistically significant differences. The significance level was set at $P < .05$ (Table 2).

RESULTS

In G1, canines experienced the largest intrusive forces, 0.92 N on the left and 0.69 N on the right, while the central and lateral incisors experienced -0.20 N and -0.17 N extrusive forces, respectively. The left and right first premolars received -0.52 N and -0.22 N, respectively, and the second premolars endured a



a b

Figure 1. A resin model printed by a 3D printer for manufacturing the corresponding aligner (a); the aligner was trimmed and numbered (b).

mean extrusive force of –0.44 N, indicating that the premolars were the major anchorage teeth and incisors also provided anchorage for canine intrusion.

In G2, aligners exerted 0.17 N and 0.23 N intrusive forces on lateral and central incisors, respectively. Mean extrusive forces of –0.57 N and –0.07 N were measured on the left and right canines, which acted as anchorage teeth along with the premolars.

In G3, canines experienced larger intrusive forces (0.28 N) than incisors (0.11 N on the lateral incisors and 0.16 N on the central incisors), while the first premolars had the largest extrusive forces on both sides. Intrusive forces on canines were only one-third of that on G1 canine. Intrusive forces on the incisors were the same as that of G2 on the incisors.

The central incisors experienced no statistically significantly different forces with G4 than with G3 aligners. However, the lateral incisors and canines experienced no intrusive forces, despite the intrusive activation of 0.15 mm and 0.1 mm, respectively.

With the same level of activation, canines had statistically significantly larger intrusion forces with G1 than with G3 aligners, while there was no statistically significant difference in the intrusion forces on incisors among the different groups. Premolars were subjected to the largest extrusive forces with G3 aligners.

DISCUSSION

Orthodontics uses forces and moments to move teeth. In this in vitro study, insights were made into the forces exerted by clear aligners during mandibular intrusion by using multiaxis force and torque sensors. With the same preset 0.2-mm activation during equivalent combined intrusion, canines experienced

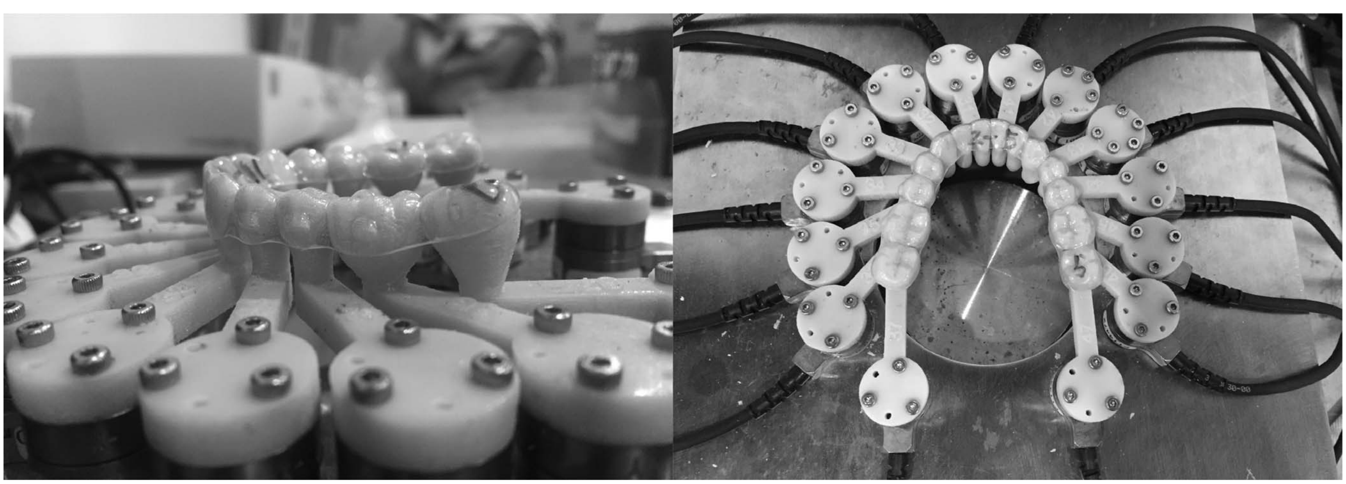


Figure 2. Aligner test setup.

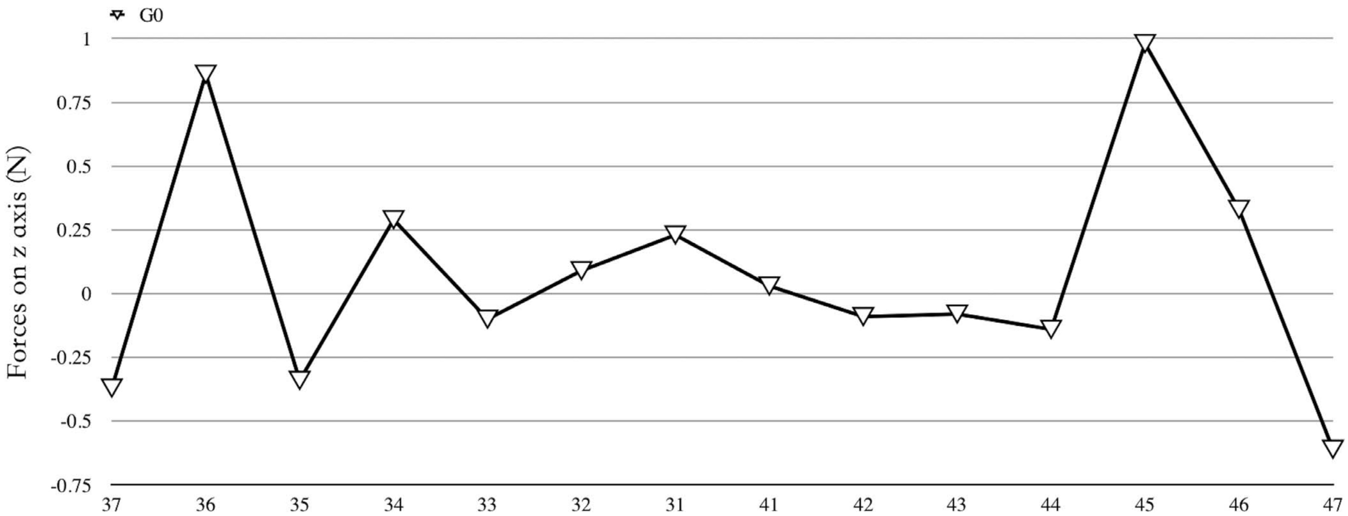


Figure 3. Mean forces on the *z*-axis of G0 aligners.

larger forces than incisors, and premolars received the largest extrusive force. Canines had the largest intrusive forces when intruded alone, but for lower incisors, the forces were not significantly different among the various groups exposed to the same amount of activation. Forces exerted by the G4 aligners showed consistent mechanical distribution with activation; however, lateral incisors and canines tended to experience extrusive forces demonstrating that it was less effective for intruding all targeted teeth. The results suggested that intruding anterior teeth using different activations concurrently may not be recommended. The aligners could deliver forces quite well in the vertical dimension, and the final magnitude of force delivered was the result of the actual activation of each tooth; this activation was a combination of the preset activation, attachment, neighboring tooth movement, and material properties. The biomechanical properties of aligners are complex, as they are closely related to the material properties, thickness, production process, designed tooth movement sequence, activations, shape, position and bonding accuracy of the attachments, fitting accuracy of the aligner to the teeth and attachments, and patient cooperation.[17–19]

In this study, 0.8-mm transparent plastic material was used to vacuum form the clear aligners with an amount of activation ranging from 0.1 mm to 0.2 mm. It has been reported that more than 1 mm anterior intrusion per arch is difficult to achieve with an aligner alone, and attachments or altered aligner geometries are necessary to improve the treatment outcome.[2] In this study, conventional transverse rectangular attachments were placed on premolars and the first molar on each side to enhance accuracy of the fit. Extrusive forces were concentrated on premolars, and these produced statistically significant changes among different intrusion patterns. Rectangular attachments on premolars are necessary and effective during intrusion.

Different invisible orthodontic suppliers have recommended different amounts of activation[13]; for the material used in this study, activation of 0.2 mm resulted in maximum intrusion force on the canines of less than 1 N, when the canines were intruded alone. As force decays after repeated loading, especially in the oral environment, the activation amount should be adjusted according to material attenuation and the wear period to ensure efficient tooth movement. The thickness of the thermoplastic material and level of deflection of tooth movement should also be considered to achieve physiological tooth movement.[13,19]

The results were obtained using a measuring device that was based on force/moment sensors and 3D-printed resin teeth. The test setup was employed previously,[13,14,17,20,21] but, at that time, could only measure the force on one tooth at a time. The setup in this study allowed documentation of forces on the whole dentition and made it possible to elucidate aligner mechanics.

The force magnitudes achieved with the aligners differed even within the same group (Figure 4), partly because the aligners were produced by thermoforming and partly because of the accuracy of aligner placement by the researcher. To minimize operating error, the process for loading all aligners was accomplished by one researcher.

Orthodontic deep-bite correction involves extrusion of posterior teeth, intrusion of incisors, or both.[22] The treatment choice depends on various factors, such as incisor display and vertical dimension.[23] Miniscrews and segmented arches are recommended, as these techniques can provide intrusion forces close to the center of resistance.[24] Clear aligners have advantages

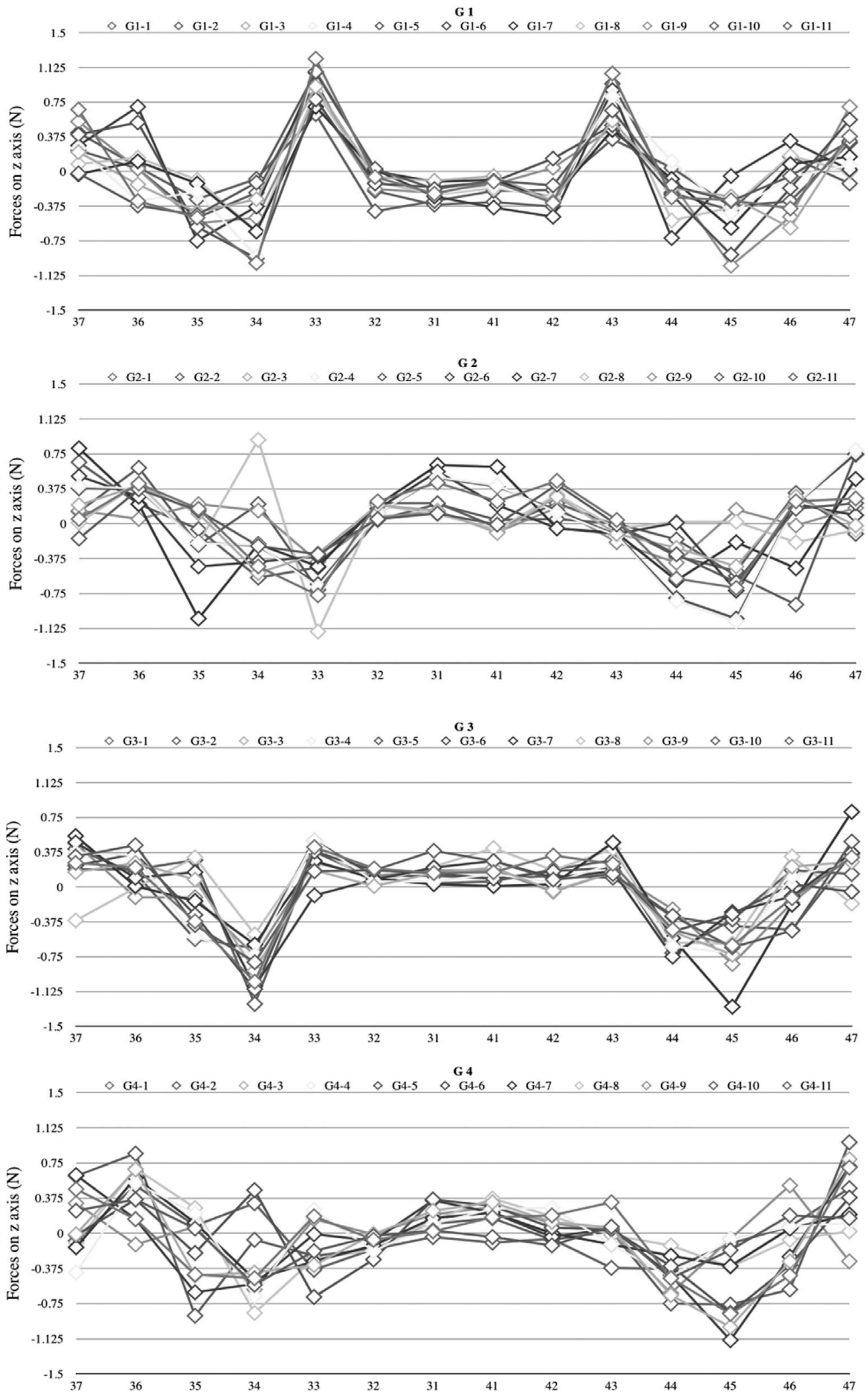


Figure 4. Line chart of forces on the *z*-axis generated by four groups of aligners.

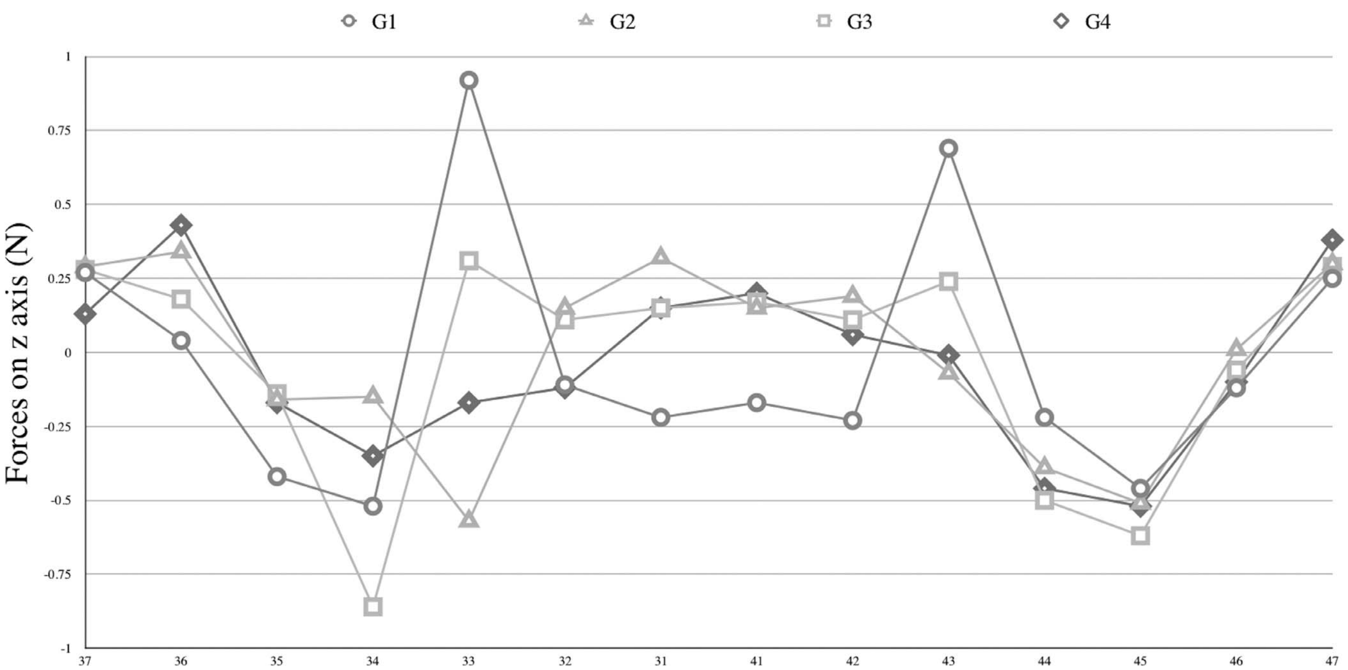


Figure 5. Mean forces on the *z*-axis of the four groups of vertical movement aligners.

for intruding mandibular anterior teeth. With a computer-aided pretreatment tooth movement plan, the space required for intrusion can be accurately designed and calculated. With precise interproximal reduction or extraction and restrictions of the anterior boundary, incisors would not incline labially. In addition, aligners cover the entire dentition as an overlay appliance, thereby preventing extrusion of posterior teeth. Although a clear aligner may exert relatively large forces on the dentition in the first few days, root resorption is reportedly not different from that observed with conventional orthodontic appliances.[25,26]

Table 2. Comparison Among Groups

Tooth No.	Fz (n) G1 Mean (SD)	G2 Mean (SD)	G3 Mean (SD)	G4 Mean (SD)
37[e]	0.27 (0.22)	0.29 (0.28)	0.28 (0.28)	0.13 (0.13)
36[e]	0.04 (0.34)[bd]	0.34 (0.15)[a]	0.18 (0.17)	0.43 (0.29)[a]
35[e]	−0.42 (0.21)	−0.16 (0.35)	−0.14 (0.32)	−0.17 (0.38)
34[e]	−0.52 (0.33)	−0.15 (0.43)[c]	−0.86 (0.23)[bd]	−0.35 (0.41)[c]
33[e]	0.92 (0.19)[bcd]	−0.57 (0.25)[acd]	0.31 (0.18)[abd]	−0.17 (0.28)[abc]
32[e]	−0.11 (0.13)[bc]	0.15 (0.07)[ad]	0.11 (0.06)[ad]	−0.12 (0.09)[bc]
31[f]	−0.22 (0.08)[bcd]	0.32 (0.20)[a]	0.15 (0.10)[a]	0.15 (0.13)[a]
41[f]	−0.17 (0.10)[bcd]	0.15 (0.24)[a]	0.17 (0.12)[a]	0.20 (0.15)[a]
42[e]	−0.23 (0.18)[bcd]	0.19 (0.17)[a]	0.11 (0.11)[a]	0.06 (0.13)[a]
43[f]	0.69 (0.24)[bcd]	−0.07 (0.07)[ac]	0.24 (0.12)[abd]	−0.01 (0.17)[ac]
44[e]	−0.22 (0.24)[c]	−0.39 (0.29)	−0.50 (0.17)[a]	−0.46 (0.18)
45[e]	−0.46 (0.28)	−0.51 (0.38)	−0.62 (0.29)	−0.52 (0.41)
46[e]	−0.12 (0.30)	0.01 (0.38)	−0.06 (0.26)	−0.1 (0.32)
47[e]	0.25 (0.25)	0.3 (0.34)	0.29 (0.26)	0.38 (0.39)

Significantly different from [a] group 1, from [b] group 2, from [c] group 3, and from [d] group 4 on the same tooth.
[e] Bonferroni's test, $P < .05$.
[f] Dunnett's T3, $P < .05$.

An optimal external force system is key to orthodontic treatment, as controlled tooth displacement is an outcome of surrounding bone structure remodeling under continuous orthodontic force.[27] Saxena et al.[28] found a mean rate of 0.9 mm per month for the canines and 0.7 mm per month for the incisors exposed to the same force. However, it was observed clinically that canines are more difficult to intrude than incisors because of longer roots and more periodontal membrane area. To date, there is no consensus on the magnitude of optimal forces for different teeth,[29,30] and there may also be interindividual fluctuations because of different growth patterns, sex, or age. Orthodontists agree that optimal intrusion forces of tooth movement for canines and incisors may differ.

The best clear aligner treatment protocol to accomplish intrusion in a shorter period of time is to exert optimal intrusion force on the target teeth while maintaining stability of the anchorage teeth. In G3, canines experienced significantly reduced intrusive forces compared with G1 while premolars had larger extrusive forces. To guarantee the optimal intrusive force on canines, premolars must experience extremely large extrusive forces as aligners relaxed quickly during the first few days. In addition, incisors can be intruded only when canines are intruded in G3. In certain cases (for example, in an adult male with long roots, high bone density, or in severe deep overbite cases), it may be better to intrude canines and incisors separately. This is because the intrusive forces on canines or incisors are more concentrated and the first premolars can withstand the extrusion force and be stabilized for providing anchorage. However, for patients with attachment loss, combined intrusion of anterior teeth may be more achievable. This protocol may correct deep overbite more effectively in patients with attachment loss. Treatment protocols need to be individualized, involving an optimal combination of material, planning, activation, attachment, and patient compliance.

The results of this study provide some insight into clinical treatment design. However, the study had some limitations. First, the intraoral environment and periodontal ligaments were not simulated in this study because of limitations of the experimental conditions. Second, only one protocol was used for the attachments. Third, the resin model used in the test showed more rough surfaces than actual teeth. Accordingly, with the development of a wireless and waterproof micro-stress sensor system and a more complete and thoroughly designed tooth movement plan, it would be possible to obtain more accurate results in a future in vivo study.

CONCLUSIONS

- In this study, the intrusive forces of aligners using different intrusion patterns on mandibular anterior teeth were measured and analyzed. Actual aligner activation on each tooth, which was closely related to the designed activation, shape, and position of the attachment, and relative movement of the adjacent teeth influenced the final intrusion force.
- With the same activation, canines experienced the largest intrusion force when intruded alone with aligners. During combined intrusion, canines and incisors received different forces, and the first premolars experienced the largest extrusive forces.
- Intruding anterior teeth with different amounts of activation concurrently did not exert effective intrusion forces on all target teeth.

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