

Efficacy of in-house clear aligner therapy mechanics on root torque: an in-vitro study

Rüveyda Doğrugören, Kübra Gülnur Topsakal, Gökhan Serhat Duran, Berat Serdar Akdenizv and Serkan Görgülü

Department of Orthodontics, Gulhane Faculty of Dental Medicine, University of Health Sciences, Ankara, Türkiye*

Background: This study aimed to evaluate the torque effectiveness of different attachment types and power ridges used in clear aligner therapy (CAT) on the upper lateral incisors.

Methods: A typodont model simulating oral conditions was developed. Two hundred lateral incisor samples were divided into five groups based on attachment types and clear aligner modifications: no attachments (NA), horizontal ellipsoid attachment (HEA), vertical ellipsoid attachment (VEA), buccal power ridge (BPR), and buccal and palatal power ridge (BPPR). Subsequently, a 5° palatal torque moment was applied to the lateral incisors. In-house clear aligners were inserted, and 3D scanning was performed after each aligner step. Post-treatment 3D models were compared with pre-treatment models. The lateral incisors were assessed for torque, tipping, and rotational movements.

Results: The HEA group (41.6%) and the BPPR group (40.8%) showed significantly higher torque effectiveness than the NA group (20%) when 5° of torque was delivered. The planned movement was approximated when 1° and 2° of torque were applied in the NA group (114% and 98%, respectively). The NA and BPR groups showed the highest loss of anchorage.

Conclusions: When more than 3° of torque was applied, HEA and BPPR were more effective than NA in achieving the CAT's planned torque of the upper lateral incisors, although with an efficacy rate of approximately 40%.

(Aust Orthod J 2024; 40: 13 - 24. DOI: 10.2478/aoj-2024-0003)

Received for publication: December, 2023

accepted: January, 2024.

Rüveyda Doğrugören: ruveydadogrugoren@gmail.com; Kübra Gülnur Topsakal: gulnurbarut@hotmail.com; Gökhan Serhat Duran: gokhans_d@hotmail.com; Berat Serdar Akdeniz: bsakdeniz@hotmail.com; Serkan Görgülü: serkan.gorgulu@sbu.edu.tr

Highlights

- It is challenging to achieve torque movement using CAT.
- When less than 3° of torque was required, additional mechanics were not necessary.
- BPPR and HEA showed higher effectiveness when 5° of torque was applied.
- The efficacy of BPR was similar to that of NA.

Introduction

Clear aligner therapy (CAT) is a popular contemporary alternative to traditional fixed orthodontic treatment

and lingual orthodontics.^{1,2} Researchers have reported a higher preference for CAT over lingual fixed treatment due to the difficulties and costs associated with the fixed appliances.^{1,2} Following the advancement of three-dimensional (3D) printing technology and modelling software, the predictability of tooth movements during CAT has improved, leading to the increasing popularity of this treatment appliance.^{3,4}

Although CAT serves as an alternative to conventional bracketed appliance systems, certain tooth movements performed in fixed treatment may not be successfully achieved using clear aligners.⁵ Importantly, the effectiveness of orthodontic treatment can vary depending on factors related

to the patient's compliance, the presence of saliva, anatomical variations of the teeth, and the condition of the surrounding oral tissues (the health of gingival tissue and bone density).⁶ To better evaluate the effectiveness of specific movements and mechanical aids, it is preferable to isolate these factors from other variables by conducting *in vitro* studies based on standardised criteria. However, due to the flexibility of the clear aligner materials and production methods, achieving desired movements may require additional mechanical aids in the form of attachments, altered aligner geometry, and intraoral elastics. Importantly, while these aids are advertised as improving treatment efficacy, there is limited and sometimes contradictory evidence supporting these claims. As an example, power ridges may not have a positive impact and could potentially hinder the achievement of prescribed tooth movements.⁷ Attachments are used to improve the aligner's 'grip' on a tooth and aid in the application of force vectors for the planned movement. Torque is a challenging tooth movement using CAT, and commonly, horizontal attachments of various shapes placed on teeth, or power ridges placed in the clear aligner, are used as auxiliary mechanics to achieve effective movement.^{8,9}

Few studies have investigated the effectiveness of torque application on anterior teeth during CAT. In an *in vitro* study, Simon et al.¹⁰ evaluated the effects of horizontal ellipsoid attachments (HEAs) and power ridges on CAT torque movement and reported that the mechanics were effective in achieving torque movement for the anterior teeth. Gaddam et al.¹¹ evaluated the effectiveness of Invisalign treatment and found reduced efficacy in buccal crown torque movement, particularly for the upper lateral incisors. Jiang et al.¹² assessed incisor tooth movement in patients wearing clear aligners and reported incisor torque efficacy to be 35.21%. Sandhya et al.¹³ assessed torque movement in maxillary central incisors using a finite element analysis model and reported that the HEA was more effective at torque movement than other applications. However, it is difficult to assess *in vivo* changes attributed to torque effects due to complex intra- and inter-arch relationships, and finite element analysis provides limited data about the clinical reality. No previous study has been found that evaluated the effect of buccal power ridges (BPRs), buccal and palatal power ridges (BPPRs), and ellipsoid attachments on torque movement in addition to their impacts on adjacent teeth.

Therefore, it was aimed to evaluate the efficacy of different types of attachments and power ridge designs in crown and root movement and inclination of the lateral incisors in a novel controlled clear aligner typodont simulation.

Materials and methods

The sample size was determined by conducting a power analysis (G*Power 3.1.9.7 software). More than 95% power was calculated when a total of 200 samples were included at an alpha level of 0.05 and an effect size of 0.40. A total of two hundred samples were divided into five equal groups ($n=40$ in each) according to the attachment types and modifications used on the upper lateral incisors: A control group without an attachment (NA), a horizontal ellipsoid attachment (HEA), a vertical ellipsoid attachment (VEA), a buccal power ridge (BPR), and a buccal and palatal power ridge (BPPR).

A typodont model (M0; Nissin Dental Products, Kyoto, Japan) was scanned using an iTero Element intraoral scanner (Align Technology, San Jose, CA, USA). The scan data were transferred to Maestro 3D Dental Studio software (Maestro Dental Studio 4, AGE Solutions S.r.l., Pontedera, Italy). Horizontal rectangular attachments, with the dimensions of $1 \times 2 \times 3$ mm (depth $\times$ height $\times$ width) were digitally placed on the first molar and first premolar teeth which were used as anchorage units.¹⁴

A digital model with the anchorage attachments (M1) was exported in an STL format and transferred to Meshmixer 3D modelling software (Autodesk Research, Toronto, ON, Canada) in order to prepare a phantom jaw model. In this process, the anterior teeth, including the canines, were digitally removed to create a 'socket' designated for the placement of phantom teeth and dental wax. In contrast, the premolars and molars were retained intact to facilitate accurate superimposition of the model. A flat plane with a thickness of 2 mm, extending 2 mm horizontally from the gingiva of all teeth, was added to the model to prevent the impact of heat and steam on the clear aligner material during heating. The main digital typodont study model (MT) was exported in an .STL format for production. Two physical models were manufactured using the Anycubic Mono X 6K 3D LCD printer (Shenzhen Anycubic Technology Co. Ltd, Shenzhen, China) with Anycubic ultraviolet-sensitive resin.

The M1 digital model was converted into a hollow model with a thickness of 3 mm and two physical models were 3D printed. A jig was prepared on the physical models using a silicone impression material (Aquasil soft putty, Dentsply Co., Charlotte, NC, USA). Typodont wax (RM-3 type pink wax, Nissin Dental Products, Kyoto, Japan) was adapted to mimic the periodontal tissue in the anterior region of the MT model. The silicone jig was used to place the phantom teeth (Simple Root Tooth Model, Permanent Tooth [A5A-200], Nissin Dental Products, Kyoto, Japan) in their original positions on the MT model. The MT model with the incisors and modelling wax was scanned and saved as the baseline model with a designated number. These steps were repeated 20 times for each group. Five groups were planned for the production of the clear aligners, incorporating 1° change increments for each group.

A further five digital models were created for each group, again incorporating 1° torque increments for every model, using Maestro 3D Dental Studio software (Maestro Dental Studio 4, AGE Solutions S.r.l., Pontedera, Italy). Attachments were placed using the same clear aligner design software. The dimensions of the horizontal and vertical ellipsoid attachments in the HEA and VEA groups were 3 × 2 mm and 1 mm in depth. Attachments were placed in the middle crown third of the lateral incisors.

A power ridge design was created using 3D modelling software (Blender 3.2.2, Blender Foundation, Amsterdam, Netherlands). Semi-cylindrical indentations with the dimensions of 0.4 × 1.5 × 3.5 mm (depth × height × width) were placed at the mid-point of the mesiodistal aspect, 1.7 mm from the gingival margin on the buccal side in the BPR group and on the buccal and palatal sides in the BPPR group.¹⁵

All prepared models were 3D-printed from the resin material, post-processed using isopropyl alcohol, and cured under ultraviolet light. In total, 100 clear aligners were fabricated using PETG thermoplastic clear aligner material (CA Pro+, Scheu-Dental GmbH, Iserlohn, Germany) using a thermoplastic forming machine (Ministar, Scheu-Dental, Germany).

A novel mechanism was designed to facilitate the experiment (Supplementary Figure 1). A heat-resistant polycarbonate tray and heating mechanism were used to keep the water at a specific temperature. The typodont model was designed with circular cut-outs to allow the heated water to affect the typodont

wax. The tray's cover was trimmed to a depth at which the models were immersed in the heated water with the tooth crowns positioned above the tray so that the heat used to soften the wax could not penetrate the cover and affect the mechanical properties of the thermoplastic aligner material. The temperature of the aligners during the experiment was approximately 30°C.

Clear aligners were placed on the typodont model, and, according to the user instructions, was immersed in 57.5 °C water for 10 min to ensure that the wax surface temperature reached the desired value^{16,17} and subsequently maintained using a thermostat. After heat application, the models were immersed in cold water for 5 min according to the manufacturer's instructions to solidify the wax after which, the aligners were removed and the models scanned using an intraoral scanner.

To accurately measure tooth movement, 3D scans of the phantom teeth and their roots were digitally aligned with the crown surface of each model. The incisal edge, mesio-incisal point, and disto-incisal point of the crowns were selected for three-point alignment. Aligned roots and crowns in the typodont model were exported as a single combined 3D structure. The combined models in each group were imported into GOM Inspect Professional software (GOM, 2018, Braunschweig, Germany) for alignment. Premolars and molars, which were not segmented and remained stable, were marked on both models for alignment. The alignment was performed using a local best-fit option over the posterior region.¹⁸ The incisal edge, root apex, and mesial point were marked on the anterior teeth. Lines were created from the incisal midpoint to the apex of the teeth under investigation and used to measure the angular change of tipping and torque movements between the models (Figures 1A and 1B). For rotation detection, a line was created between the incisal edge and mesial corner, and the inter-line rotation angle was measured (Figure 1C). An experienced orthodontist (R.D.) repeated 20% of the measurements after 2 weeks, and the consistency between the measurements was determined. An overview of the workflow is provided in Figure 2.

Statistical analysis

A Shapiro–Wilk test showed that the data did not conform to a normal distribution. A Kruskal–Wallis *H* test was used to analyse the differences between the

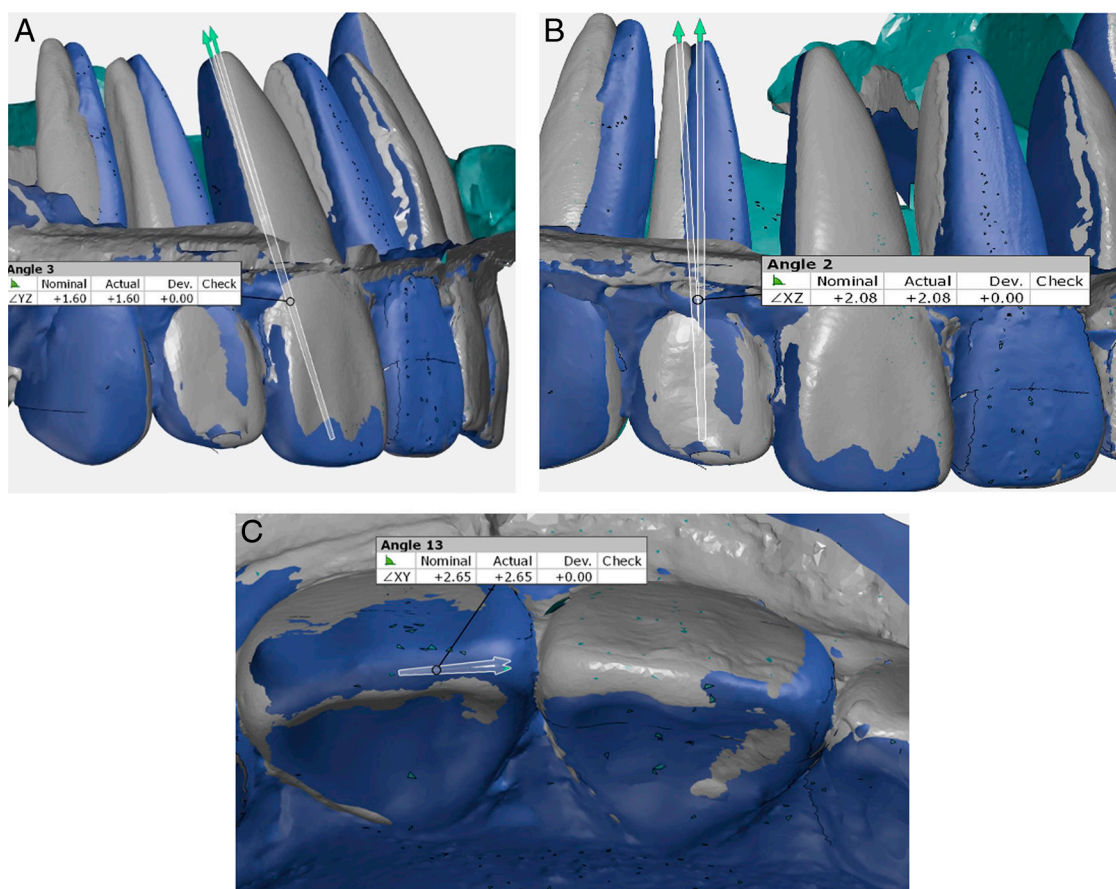


Figure 1. A, Angle created for measuring torque movement using GOM Inspect Professional software (GOM, 2018, Braunschweig, Germany). B, Angle created for measuring tipping movement. C, Angle created for measuring rotation movement.

groups, and a Mann–Whitney U test was applied for post hoc comparisons. Measurement consistency was evaluated using a two-way mixed model analysis and absolute agreement type of the intraclass correlation coefficient (ICC) with a 95% confidence interval. The statistical analyses were performed using jamovi software (Version 2.3, Sydney, Australia)¹³ at a significance level of 0.05.

Ethics approval information

Ethical approval was not required for this study since it was not performed on human nor animal materials, and no patient data were used. The intraoral scanner was used to validate accuracy.

Results

The ICC values at 95% confidence intervals used to assess intra-rater reliability for angular measurements

were 0.89 for torque movement, 0.93 for rotational movement, and 0.84 for tipping movement. An ICC analysis was conducted to determine the accuracy between the initial model used for superimposition and the models to which the movement was applied, and it was found that the consistency was acceptable when evaluating the inter-premolar distance. Similarly, the consistency in evaluating the inter-molar width between the models was found to be at an excellent level of intra-rater reliability.

Expressed torque

The only significant inter-group difference for the lateral incisors was found between the BPR and BPPR groups (1.07° and 2.15°, respectively) when 5° of torque was planned. No other statistical inter-group differences were found (Table I).

No statistical inter- or intra-group differences were found for the central incisors (Table II).

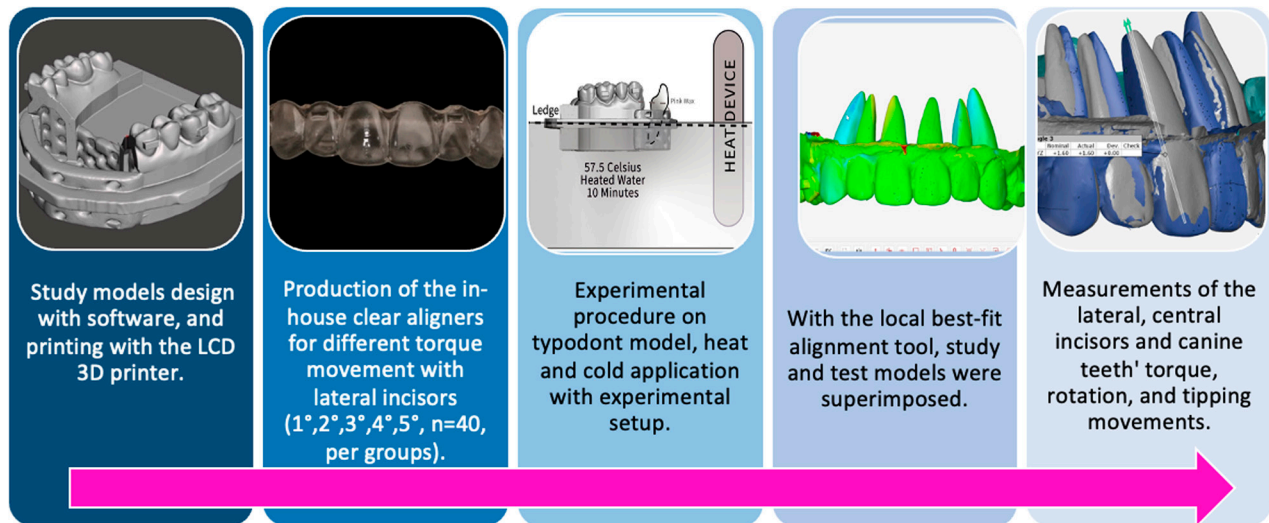


Figure 2. The flow chart of the study.

The only significant inter-group difference for the canines was found when 2° of torque was planned. There were statistically significant differences in the expressed torque values of the canines within the BPR, BPPR and HEA groups. The canines in the BPR group showed 3.69° of torque when 2° of torque was applied to the lateral incisors. The HEA and BPPR groups showed lower torque values (1.24° and 0.94°, respectively). No other significant differences were found between the groups (Table III).

The only statistical inter-group difference was found in the BPPR group between the planned torque values of 1° and 5°. When 1° torque was planned,

0.83° was expressed, while only 2.15° was expressed when 5° of torque was planned.

The canines in the BPR group also showed significant inter-group differences. Statistically different torque expressions were observed when 1° and 2° of torque were planned. No other inter-group differences were found.

The ratio between planned and expressed torque values may be considered to measure the efficacy of the system.¹⁹ The highest torque efficacy for the lateral incisors was found when 1° and 2° of torque were applied in the NA group (114% and 98%, respectively). When attempting to achieve 5° torque

Table I. Descriptive statistics and post hoc comparisons of torque values (degree) of the lateral incisor teeth

	1°	2°	3°	4°	5°	
Group	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	<i>p</i> *
Control	1.14 ± 0.85	1.66 ± 0.82	1.42 ± 0.74	1.32 ± 0.62	1.49 ± 0.42 ^{ab}	0.852
Buccal Power Ridge	1.40 ± 1.12	1.34 ± 1.02	1.32 ± 1.07	0.98 ± 0.53	1.07 ± 0.56 ^a	0.963
Buccal and Palatal Power Ridge	0.83 ± 0.40 ^A	1.16 ± 0.71 ^{AB}	1.49 ± 0.81 ^{AB}	2.04 ± 0.85 ^{AB}	2.15 ± 0.40 ^{Bb}	0.004*
Vertical Ellipsoid	1.22 ± 0.74	1.43 ± 0.76	1.33 ± 1.18	1.31 ± 0.80	1.59 ± 0.64 ^{ab}	0.644
Horizontal Ellipsoid	0.79 ± 0.70	1.25 ± 0.71	1.88 ± 1.12	1.56 ± 1.15	2.08 ± 0.96 ^{ab}	0.072
<i>p</i>	0.591	0.732	0.626	0.145	0.017*	

*There is a statistically significant difference at *p* < .05.

Different letters show statistical differences (Uppercases indicate intra-group differences, lowercases indicate inter-group differences).

SD, Standard deviation.

Table II. Descriptive statistics and post hoc comparisons of effected torque values of the central incisor teeth

	1°	2°	3°	4°	5°	<i>p</i> *
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
No Attachment	2.00 ± 1.11	1.36 ± 0.92	1.24 ± 0.95	1.23 ± 0.80	1.24 ± 1.08	0.630
Buccal Power Ridge	1.14 ± 0.67	1.27 ± 1.31	0.94 ± 0.67	1.80 ± 1.11	1.24 ± 0.73	0.486
Buccal and Palatal Power Ridge	0.91 ± 0.86	1.20 ± 0.88	1.15 ± 0.62	0.94 ± 0.48	0.99 ± 0.51	0.868
Vertical Ellipsoid	1.21 ± 0.89	1.18 ± 1.13	1.16 ± 0.95	1.37 ± 0.74	1.12 ± 0.65	0.916
Horizontal Ellipsoid	1.05 ± 0.65	0.89 ± 0.49	0.84 ± 0.77	0.93 ± 0.87	0.87 ± 0.45	0.903
<i>p</i>	0.175	0.870	0.885	0.278	0.896	

*There is a statistically significant difference at *p* < .05.

SD, Standard deviation.

movement for the lateral incisors, the highest efficacy was in the HEA (41.6%) and BPPR (40.8%) groups, followed by the VEA group (32%). The least torque movement was observed in the BPR (19%) and NA (20%) groups (Figure 3).

Rotation and tipping

The greatest rotation was expressed in the HEA group when 1° and 2° torque movements were applied to the lateral incisors (2.67° and 2.49°, respectively). The greatest rotation occurred in the NA group when 3° and 4° of torque were planned (2.53° and 2.72°, respectively). When 5° of torque was applied, the greatest rotation (4.11°) was observed in the BPPR group (Figure 4A). The greatest rotation occurred on the central incisors in

the HEA group when 1° and 2° of torque were applied to the lateral incisors (2.67° and 2.49°, respectively). For 3° and 4° of torque, the greatest rotation occurred in the NA group (2.53° and 2.72°, respectively). When 5° of torque was applied, the greatest rotation (2.88°) was observed in the BPPR group. The greatest rotation occurred for the canines in the BPR and BPPR groups when 1° of torque was applied to the lateral incisors (3.01° and 3.01°, respectively). For 2°, 3°, and 5° of torque, the greatest rotation occurred in the NA group (3.54°, 4.5° and 3.67°, respectively). When 4° of torque was applied, the greatest rotation (3.32°) was observed in the VEA group.

When torque was applied to the lateral incisor, the least tipping movement reflected on the teeth was generally observed in the HEA and BPPR groups.

Table III. Descriptive statistics and post hoc comparisons of effected torque values of the canine teeth

	1°	2°	3°	4°	5°	<i>p</i> *
Group	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
No Attachment	1.23 ± 0.69	2.12 ± 0.95 ^{abc}	1.64 ± 1.37	0.99 ± 0.60	1.78 ± 1.25	0.209
Buccal Power Ridge	1.20 ± 0.50 ^A	3.69 ± 1.43 ^{Ba}	2.88 ± 1.56 ^{AB}	1.86 ± 1.26 ^{AB}	3.10 ± 3.05 ^{AB}	0.015*
Buccal and Palatal Power Ridge	1.78 ± 0.92	0.94 ± 0.57 ^b	1.04 ± 0.62	1.76 ± 1.90	1.21 ± 1.15	0.506
Vertical Ellipsoid	0.90 ± 0.62	1.83 ± 1.34 ^{abc}	0.85 ± 0.76	1.86 ± 1.78	1.33 ± 1.31	0.278
Horizontal Ellipsoid	1.52 ± 1.00	1.24 ± 0.63 ^c	1.57 ± 0.89	1.10 ± 0.77	1.51 ± 1.30	0.870
<i>p</i>	0.297	<0.001*	0.034	0.698	0.324	

*There is a statistically significant difference at *p* < .05.

**Different letters show statistical difference (Uppercases indicate intra-group differences, lowercases indicate inter-group differences).

SD, Standard deviation.

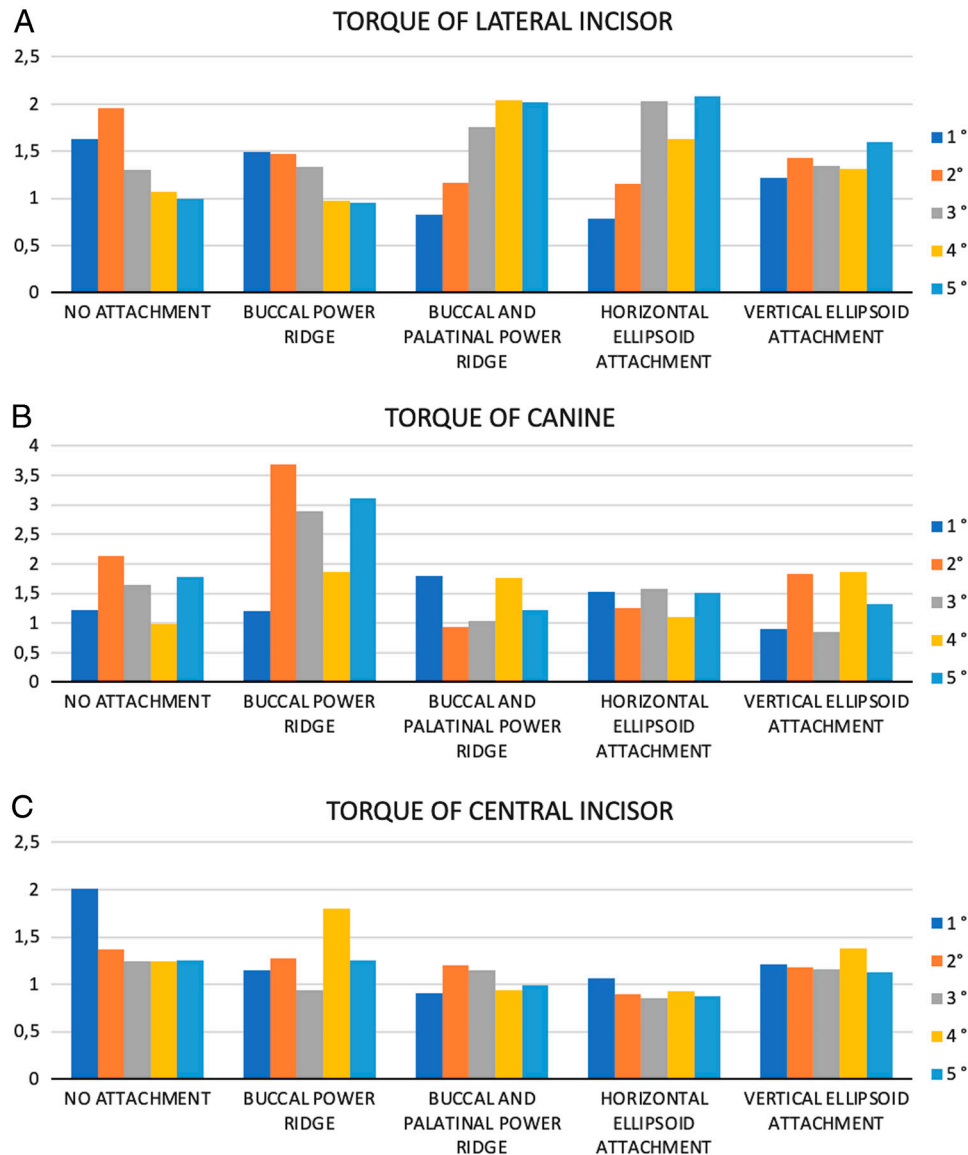


Figure 3. Column chart showing the effectiveness of torque movement at different degrees. A, Distribution of torque values in lateral incisor teeth based on degree and mechanism type. B, Distribution of torque values in canine teeth based on degree and mechanism type. C, Distribution of torque values in central incisor teeth based on degree and mechanism type.

When 1° torque was applied, the maximum tipping movement was observed in the HEA group (2.42°). When 2° torque was applied, the NA group exhibited the greatest tipping movement (2.15°). When 3° torque was applied, the VEA group showed the greatest tipping movement (3.13°). When 4° torque was applied, the BPR group exhibited the greatest tipping movement (2.35°). When 5° torque was applied to the lateral incisor, the least tipping was observed in the BPPR group (1.16°), while the greatest tipping (2.34°) was observed in the VEA group (Figure 4B).

The changes occurring in the anterior region as a result of applying 5° of torque to the lateral teeth are shown in Figure 5 using a local best fit.

Discussion

Clear aligners have been shown to be an effective tool to effect orthodontic treatment. The efficacy of aligners is noted to vary according to the desired direction of tooth movement.²⁰ Sfondrini et al.²¹ compared the buccolingual inclination in conventional bracket systems and clear aligners and

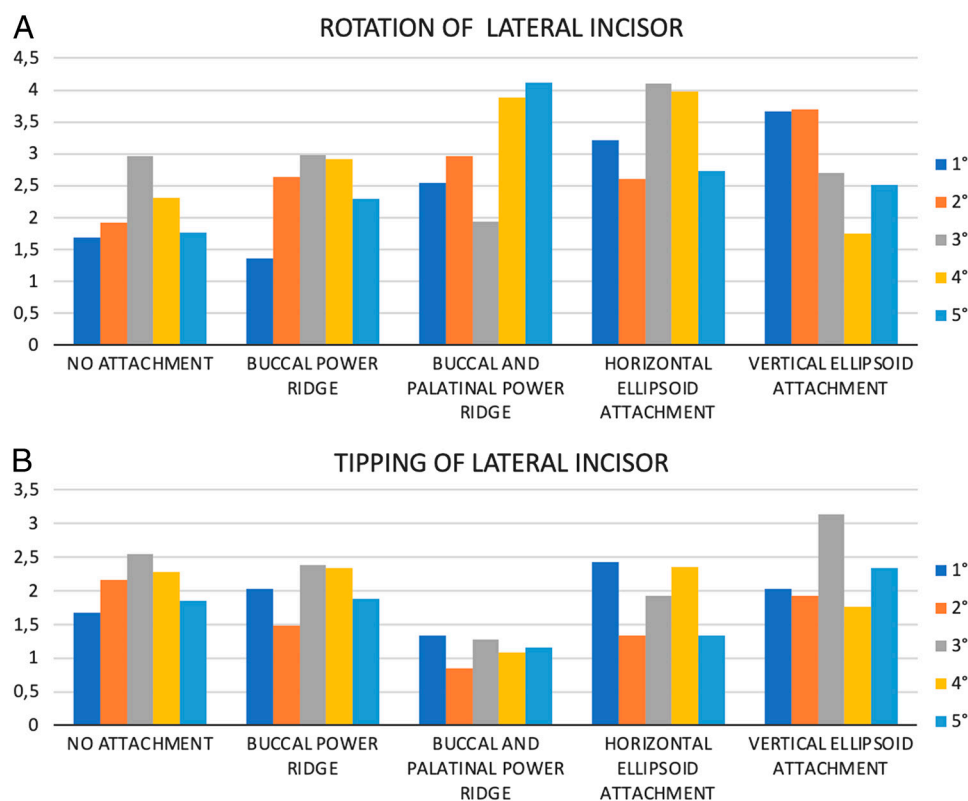


Figure 4. The table presents side effects resulting from applying torque movement at different degrees to the lateral incisor teeth. A, Distribution of rotation values in the lateral incisor teeth based on degree and mechanism type. B, Distribution of tipping values in the lateral incisor teeth based on degree and mechanism type.

found that, although the lowest torque values were observed using clear aligners, there was no statistically significant difference between the treatment options. Jiang et al.¹² reported that the incisors had a 55.58% efficacy rate when moved sagittally. Root movements, particularly torque movement, pose challenges during clear aligner treatment, as movements may not always occur as planned, and require additional mechanics.²² In the present study, it was aimed to evaluate the effectiveness of torque, which is a challenging movement using clear aligner treatment and compare the results of different torque values.

In vivo studies have difficulties in achieving standardisation due to factors related to the alveolar bone's response to tooth movement, saliva acting as a filler between the aligner and teeth, potential changes dependent on the duration of aligner usage, and patient-related factors (e.g., the duration of aligner usage, anatomical variations, and type of anomaly present).¹⁴ However, when the necessary conditions and standardisation are produced, valuable results with clinical applications can also be obtained from

in vitro studies. The present in vitro study facilitated root displacement detection by aligning a scanned tooth's crown surface with its corresponding surface on the model. Based on this information, a typodont model produced by a 3D printer was preferred, so that the posterior teeth were fixed, and the applied force could be distributed to the anterior region.

Although the BPPR and HEA contributed to the torque movement of the lateral incisors when 5° of torque was applied, a limited level of effectiveness was observed in achieving the desired torque movement. The most effective application after the BPPR and HEA was the VEA model. However, the application of a power ridge solely from the buccal side did not yield consistent results and showed similar efficacy as the model without attachments. While dual force application may enhance torque transmission compared to unilateral force application, outcomes could vary depending on dental anatomy, material properties, and the magnitude of the applied forces.⁶ However, increasing the force might cause undesired intrusion of the tooth, known as a 'watermelon seed

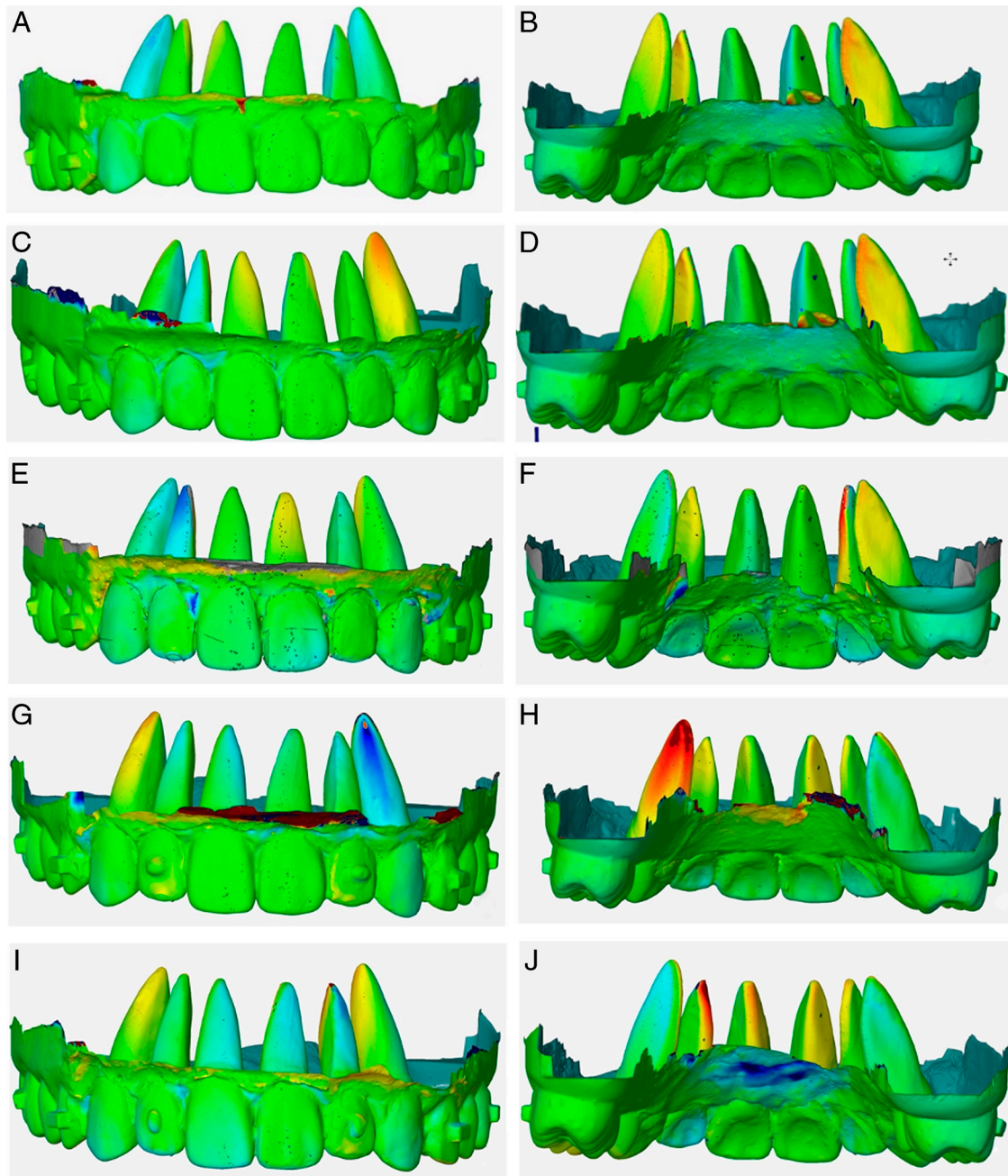


Figure 5. Examples of buccal and palatal interferences in models with 5° torque movement. A-B, Image of buccal and palatal interference in the group without attachments. C-D, Image of buccal and palatal interference in the buccal power ridge group. E-F, Image of buccal and palatal interference in the buccal and palatal power ridge group. G-H, Image of buccal and palatal interference in the horizontal ellipsoid attachment group. I-J, Image of interference in the vertical ellipsoid attachment group.

effect'. This effect results in inadequate coverage of the clear aligner on the tooth surface during dual-force application, as the distortion of the appliance triggers an intrusive force on the tooth.^{7,22,23} Simon et al.¹⁰ reported a torque efficacy of 49.1% for the HEA. Similarly, an average movement efficacy of 41.6% was observed in the HEA group in the present study.

The differences in efficacy rates reported between the present study's sole BPR application (19%) and the 51.5% efficacy rate reported by Simon et al.¹⁰ could be attributed to factors identified as the different study settings (in vitro versus in vivo), disparities in the materials utilised, and potentially other influential variables beyond differences in tooth type. Jiang et

al.¹² using 10° of torque, reported an efficacy rate of 31.7% involving the maxillary lateral incisors. Hong et al.,¹³ in a CBCT study, found an efficacy rate of 48.9% affecting the lateral incisors.²⁴ The efficacy of the power ridge applied from both the buccal and palatal sides was 40.8% in the current study. Sandhya et al.,¹³ in their study comparing this application with ellipsoid attachments, found that the displacement of roots was similar using a power ridge and an HEA, which aligns with the findings of the present study.

In considering the differences observed between minor torque (1° or 2°) and major torque (5°) efficacy among different attachment groups, it was hypothesised that, at minor torque levels, the NA and BPR groups might have exhibited relatively higher efficacy due to the aligner's better adaptation or closer fit to the tooth surface. This adaptation could result in more effective force transmission to the tooth compared to situations involving attachments or power ridges.

In contrast, at higher torque levels (5°), the attachment or power ridge groups might have faced challenges due to the increased force required to achieve the prescribed torque movement. This increased force application might have led to a compromised fit or adaptation of the aligner, potentially causing the aligner to move away from the tooth surface and result in reduced efficacy of torque expression. Additionally, it is possible that the VEA, which is perpendicular to the direction of the torque force, may have been less effective than the HEA.

When 5° torque movement was applied to the lateral incisors, maximum rotational movement was observed in the BPPR group. When evaluating the rotational movement as a side effect of torque, it was observed that the NA group had the least rotational movement. When evaluating the tipping accompanying torque application, it was observed that the VEA group had the greatest tipping movement. The choice of application can vary depending on clinical expediency when torque movement is planned for the lateral incisors. The clinician may prefer not to use attachments when applying low levels of torque.

Nonetheless, in instances in which rotational movement is not intended, the implementation of BPPRs may be considered a more suitable approach. The force applied to a tooth, depending on the system used, can have an effect throughout the entire arch. The present study observed that, when incisor torque movement was applied to the models, the canines

showed the most pronounced movement. This could be attributed to the position and the rounded root structure of the canines, which may cause buccal root torque of the lateral incisors due to the movement applied. Additionally, since the posterior teeth were stabilised by the system, the force that should have been distributed between the posterior teeth may have been concentrated at the canines. The group that received the BPPR exhibited the highest torque and tipping movements in the canines. This could be due to the lack of palatal support of the aligner in the lateral incisor area, causing the aligner to move away from the teeth, and in the case of the canines, exert more pressure on those teeth.

When evaluating the effect of torque movement on the anterior teeth, it was observed that, when 5° of torque was applied to the lateral incisors, all groups showed greater rotation of the canines than of other teeth. When applying torque to the lateral incisors, the addition of attachments to the canines can increase the effectiveness of lateral incisor torque and limit the rotation movement of the canines. Moreover, as the effectiveness of torque increased for the lateral incisors, rotational movement also increased. When torque movement is desired, depending on the clinical situation, the stability of the aligner can be increased by adding attachments to neighboring teeth to prevent unwanted rotation.

Although torque movement of the central incisors, occurred as a result of reciprocation, the movement was not as pronounced as that seen for the lateral incisor and canine teeth. The root anatomy of the central incisors may provide greater resistance to the deformations that may occur using clear aligners. Additionally, it may be considered that the anchorage of each central incisor is potentially reinforced through biomechanical interdependence with its adjacent counterpart, suggesting a synergistic stabilising effect in resisting the torque movements. Generally, there was not a substantial amount of tipping observed involving the central incisors. Of the groups that received 5° of torque movement, the greatest rotation was observed in the BPPR group. When applying torque movement to the lateral incisors, the use of a rotation-preventing attachment on central incisors may be beneficial.

This was an *in vitro* study, and so the reactions of the surrounding dental tissues to tooth movement could not be evaluated. Additionally, it is important

to consider the anatomical features of the canines and their position at the corners of the arch, may have played a role in the observed adverse effects. The intricate interaction of forces could have resulted in unintended movements of the canines, even though the primary objective was to correct the lateral incisors. The study of torque movement observed in the anterior teeth may also occur in the posterior teeth. In future studies, the effects of higher levels of torque movement applied to the anterior teeth affecting posterior teeth should be evaluated. Higher levels of torque movement can alter the effectiveness of the applied mechanics.

Conclusion

1. The effectiveness of torque applied to the lateral incisors by clear aligners was limited.
2. HEAs and BPPRs were the most reliable when 5° of torque was planned for the upper lateral incisors. However, it is crucial to note that, even with these attachment types, movement efficacy remained only 40%.
3. Power ridges and attachments should be used when more than 5° of torque is planned for the upper lateral incisors.
4. BPPRs, showed the highest amount of rotation but the lowest amount of tipping as side effects.

Conflict of interest

The authors declare that there is no conflict of interest.

Funding

This study was supported by the University of Health Sciences Gulhane Faculty of Dental Medicine Scientific Research Project Commission.

Authors contributions

R.D: Investigation, Resources, Data curation, Writing- original draft, Experimental analysis, Statistical analysis. K.G.T: Validation, formal analysis, data curation, writing-original draft, writing-review & editing, visualisation. G.S.D: Conceptualisation, methodology, supervision, project administration. B.S.A: Software, validation, formal

analysis, visualisation. S.G: Conceptualisation, supervision, project administration.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve the readability and evaluate the grammar of the original article's language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Data availability

The data that support the findings of this research article are available from the corresponding author, upon reasonable request.

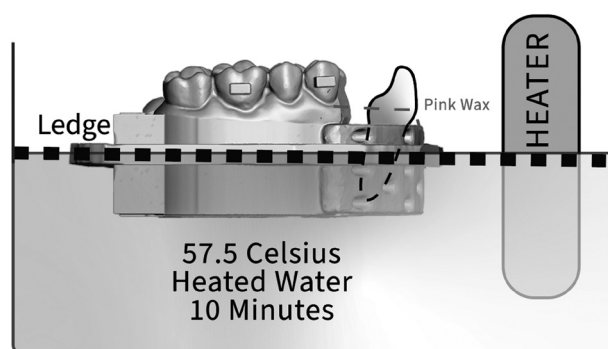
Corresponding to

Rüveyda Doğrugören, Department of Orthodontics, Gulhane Faculty of Dental Medicine, University of Health Sciences, Ankara, Türkiye, Orcid ID: 0000-0002-5916-5382, Email: ruveydadogrugoren@gmail.com

References

1. AlSeraidi M, Hansa I, Dhaval F, Ferguson DJ, Vaid NR. The effect of vestibular, lingual, and aligner appliances on the quality of life of adult patients during the initial stages of orthodontic treatment. *Prog Orthod*. 2021;22(1):1–6.
2. Alansari RA, Faydhi DA, Ashour BS, Alsaggaf DH, Shuman MT, Ghoneim SH, et al. Adult perceptions of different orthodontic appliances. *Patient Prefer Adherence*. 2019;13:2119–28.
3. Weir T. Clear aligners in orthodontic treatment. *Aust Dent J*. 2017;62:58–62.
4. Bruni A, Serra FG, Gallo V, Deregibus A, Castroflorio T. The 50 most-cited articles on clear aligner treatment: a bibliometric and visualized analysis. *Am J Orthod Dentofacial Orthop*. 2021;159(4):e343–62.
5. Robertson L, Kaur H, Fagundes NCF, Romanyk D, Major P, Flores Mir C. Effectiveness of clear aligner therapy for orthodontic treatment: a systematic review. *Orthod Craniofac Res*. 2020;23(2):133–42.
6. Chisari JR, McGorray SP, Nair M, Wheeler TT. Variables affecting orthodontic tooth movement with clear aligners. *Am J Orthod Dentofacial Orthop*. 2014;145(4):S82–91.
7. 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(6):607–13.

8. Moya SP, Zafra JL. *Aligner Techniques in Orthodontics*. Hoboken, NJ, USA: John Wiley & Sons; 2021.
9. 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(6):728–36.
10. Simon M, Keilig L, Schwarze J, Jung BA, Bourauel C. Treatment outcome and efficacy of an aligner technique—regarding incisor torque, premolar derotation and molar distalization. *BMC Oral Health*. 2014;14:1–7.
11. Gaddam R, Freer E, Kerr B, Weir T. Reliability of torque expression by the Invisalign appliance: a retrospective study. *Australasian Orthod J*. 2021;37(1):3–13.
12. Jiang T, Jiang YN, Chu FT, Lu PJ, Tang GH. A cone-beam computed tomographic study evaluating the efficacy of incisor movement with clear aligners: assessment of incisor pure tipping, controlled tipping, translation, and torque. *Am J Orthod Dentofacial Orthop*. 2021;159(5):635–43.
13. Sandhya V, Arun A V, Reddy VP, Mahendra S, Chandrashekar BS, Aravind M. Biomechanical effects of torquing on upper central incisor with thermoplastic aligner: a comparative three-dimensional finite element study with and without auxiliaries. *J Indian Orthod Soc*. 2022;56(1):49–56.
14. Liu L, Song Q, Zhou J, Kuang Q, Yan X, Zhang X, et al. The effects of aligner overtreatment on torque control and intrusion of incisors for anterior retraction with clear aligners: a finite-element study. *Am J Orthod Dentofacial Orthop*. 2022;162(1):33–41.
15. Cheng Y, Gao J, Fang S, Wang W, Ma Y, Jin Z. Torque movement of the upper anterior teeth using a clear aligner in cases of extraction: a finite element study. *Prog Orthod*. 2022;23(1):1–11.
16. 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(3):1001–9.
17. Wax Form [ORT Various Wax] [Internet]. Kyoto: Nissin Dental Products; Kyoto, Japan.. [cited 2023 Nov 6]. Available from: https://www.nissin-dental.net/products/DentalTrainingProducts/Orthodontic/ORT_Various_Wax/index.html
18. Eric Grant Hillam. *The Analysis of the Extrusion of a Central Incisor Using Clear Aligners*. United States -- Missouri: Saint Louis University; 2021
19. Upadhyay M, Arqub SA. Biomechanics of clear aligners: hidden truths & first principles. *J World Fed Orthod*. 2022;11(1):12–21.
20. Ke Y, Zhu Y, Zhu M. A comparison of treatment effectiveness between clear aligner and fixed appliance therapies. *BMC Oral Health*. 2019;19(1):1–10.
21. Sfondrini MF, Gandini P, Castroflorio T, Garino F, Mergati L, D'Anca K, et al. Buccolingual inclination control of upper central incisors of aligners: a comparison with conventional and self-ligating brackets. *Biomed Res Int*. 2018;2018:9341821.
22. Huang AT, Huang D. *Controversies in Clear Aligner Therapy: Contemporary Perspectives, Limitations, and Solutions*. New York, NY, USA: Springer Nature; 2022.
23. Brezniak N. The clear plastic appliance: a biomechanical point of view. *Angle Orthod*. 2008;78:381–2.
24. Hong YY, Zhou MQ, Cai CY, Han J, Ning N, Kang T, et al. Efficacy of upper-incisor torque control with clear aligners: a retrospective study using cone-beam computed tomography. *Clin Oral Investig*. 2023;27:1–11.



Schematic view of the created experimental setup.