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Comparison of the predicted and achieved labiolingual inclinations of the maxillary central incisors in adult Class II division 2 malocclusions treated with clear aligners

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Objective: This study aimed to compare the predicted and achieved labiolingual inclinations of the maxillary central incisors in adult Class II division 2 malocclusions treated with clear aligners using Power Ridges® and composite attachments. **Methods:** This retrospective study included 24 patients (mean age, 26.5 ± 3.3 years). The patients had Class II division 2 malocclusion and were treated with non-extraction with Invisalign® clear aligners with either Power Ridges® or composite attachments to enhance the predictability of required change in labiolingual inclination for the maxillary central incisors. Before treatment, treatment prediction and final digital models were exported as stereolithography files and superimposed using the eModel 9.0 "Compare" software. The predicted and achieved labiolingual incisor inclinations were compared. **Results:** The mean accuracies of the achieved inclination of the central incisors were 68.3% in the Power Ridges® group and 71.6% in the attachments group. No statistically significant differences in predictability were found between the groups ($P > 0.05$). A low positive correlation was observed between the predicted inclination change and the average absolute difference between the predicted and achieved inclinations ($r = 0.19$). **Conclusions:** Predicted labiolingual inclination is not fully achieved with clear aligners in both the Power Ridges® and attachment groups. Clinicians must take measures to counteract this limitation, specifically in Class II division 2 cases.

Key words: Aligners, Digital models, Class II, Tooth movement

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INTRODUCTION

Attainment of adequate labiolingual inclination of the anterior teeth is essential for optimal esthetics, function, and stability of orthodontic treatment.[1] Crown inclination is one of the keys to normal occlusion and was defined by Andrews as the angle formed by a line perpendicular to the occlusal plane and a line tangent to the site of the bracket on the labial surface of the crown, as viewed from the proximal view.[2] Proper inclination of the anterior teeth crowns is necessary to achieve proper overbite and posterior occlusion.[2] Achieving proper inclination of the teeth would require the application of torque. Mechanically, torque can be defined as the twisting of a structure about its longitudinal axis, whereas clinically, in orthodontics, it represents the labiolingual inclination of the tooth.[3] With fixed preadjusted orthodontic appliances, twisting a rectangular archwire in a bracket slot results in rotation of the tooth around the x-axis as a result of the moment generated.[4] Torque was defined by Rauch[5] as the force required to control the movement of the roots of teeth.

One of the major challenges in clear aligner therapy is controlling root movement, including the labiolingual inclination of the incisors. To provide additional support and control during the treatment, aligner bends, pressure spots, and attachment designs have been introduced.[6] These auxiliaries are particularly useful in controlling torque and ensuring proper alignment of the teeth. The Power Ridges® from Align Technology (Santa Clara, CA, USA) are "indentations" found on the surface of the aligner to keep the aligner in place at the gingival border and apply extra pressure to certain teeth while managing the force coupling and successfully rotating the tooth around its center of resistance.[7] Attachments are made of composite material cured on the labial surface of the tooth. They provide additional points of contact for the aligner to grip the teeth, improve aligner retention, and enhance the predictability of orthodontic tooth movements.[8]

The mean accuracy of achieving torque movement with clear aligners is 42%.[9] Most authors advise overcorrection of required tooth movements with clear aligner therapy.[10,11] Kravitz et al.[12] evaluated the efficacy of tooth movements using Invisalign® (Align Technology) clear aligners. Results showed that the mean accuracy of tooth movement was 41%. A follow-up study in 2020 reported an average accuracy of 50% for all movements, showing an improvement in overall accuracy, but still falling behind the desired accuracy in the clinical setting.[13]

A systematic review investigating the effectiveness of clear aligners concluded that certain tooth movements were effective with a "low to moderate level of certainty."[14] In mild-to-moderate malocclusions, clinically acceptable incisor labiolingual inclination is achieved with clear aligners, analogous to the results of fixed appliance therapy.[14]

Jiang et al.[15] found that the overall efficacy of incisor movement was 55.58%; pure tipping, controlled tipping, and translation produced the most accurate results (72.48%), whereas torque was the least accurate (35.21%). This may have been because, during torquing movements, aligners have a tendency to lift up, making it difficult for the occlusal edge of the appliance to sit firmly against the tooth.[16] Regarding the direction of torque movement, Gaddam et al.[17] reported the under-expression of torque when incisors were planned to move in a labial direction and over-expression of torque to a limited extent when incisors were planned to move in a lingual direction. For the maxillary central incisor, the mean difference between predicted and achieved torque movements (when the crown was moved labially) was 6.43° (standard deviation = 7.09). However, their study focused on mild-to-moderate Class I malocclusions. A similar finding was also reported by Jiang et al.[15] using cone beam computed tomography, which revealed that labial root torque movement was more predictable than palatal root movement. Class II division 2 malocclusion cases are characterized by retroclined central incisors requiring significant palatal root torque, which can be considered a challenging movement.

Invisalign® claims that clear aligners can produce root movement of maxillary central incisors up to 4 mm,[7] and Power Ridges® and attachments are claimed to provide additional control and precision in moving teeth, helping proper alignment and torque control in Class II division 2 malocclusions.[6] However, there is a lack of evidence to support this claim.[18] Simon et al.[9] analyzed the influence of auxiliaries (attachments and Power Ridges®) on the efficacy of orthodontic treatments using Invisalign® and reported mean accuracies of 51.5% for incisor torque in the Power Ridges® group and 49.1% in the attachments group, with no substantial differences between the two groups.

Thus, this study aimed to compare the predicted and achieved labiolingual inclinations of the maxillary central incisors using clear aligners (Invisalign®) with Power Ridges® and composite attachments in adult Class II division 2 malocclusions and to investigate the relationship between the predicted amount of inclination change and mean absolute difference between predicted and achieved movements.

MATERIALS AND METHODS

This study was approved by the Research Ethics Committee of the University of Sharjah (approval number

REC-23-02-11-01-PG). All participants signed an informed consent form before the start of the orthodontic treatment. The sample size was calculated based on the ability to detect a clinically significant difference of 2° in torque between the attachments and Power Ridges® groups. The G*Power software (Universität Düsseldorf, Düsseldorf, Germany) indicated that a sample size of at least eight patients per group would achieve 80% power with a significance level (alpha) of 0.05.

Records of orthodontic patients treated by a single practitioner with Invisalign® clear aligners at a private practice in Dubai between 2017 and 2023 were used for this study according to the following criteria: adults (age range, 18–45 years), full permanent dentition (excluding third molars), Class II division 2 malocclusion (ANB angle > 5°, Class II half-unit molar relationship with maxillary incisor inclination to the palatal plane < 103°), treated on a non-extraction basis with Invisalign®, and completion of first set of aligners. Patients were excluded if they had combined treatment (Invisalign® with any other appliances), underwent extraction of permanent teeth, received anterior prosthodontic treatment, and had a compromised periodontium with signs of bone loss.

The records of 36 patients with Class II division 2 malocclusion were included for screening, and 12 were excluded because of incomplete records (n = 7) or noncompliance (n = 5). The final sample comprised 24 patients (15 females and 9 males).

The Clincheck® (Align Technology) software was used to study treatment sequencing and mechanics of all patients. The treatment stage and virtual tooth movement at each stage were displayed using navigation tools. Tooth movement tables were studied to determine various predicted linear and angular movements. To enhance the success of aligner therapy, staging of tooth movement with breakdown of the required movement was performed. The Procline, Intrude, Retract protocol was used for all patients.[19] All Invisalign® aligners were made using SmartTrack® (Align Technology) material with either the Power Ridge Smartforce® (Align Technology) feature or composite attachments to enhance torque expression for the maxillary incisors. Power Ridges® were indentations close to the gingival edge of the clear aligner (Figure 1), whereas composite attachments were bonded to the labial surface of the incisor (Figure 2), which were rectangular attachments (4 mm long, 2 mm wide, 1 mm thick) placed at the center of the labial surface of the maxillary central incisors. Twenty-four patients were divided into two groups: group 1 (Power Ridges®, 12 patients) and group 2 (attachments, 12 patients). In all the patients, both central incisors received either Power Ridges® or attachments.

The patients were instructed to wear their aligners for at least 22 hours per day and changed them every 2 weeks. Digital models were exported as stereolithography files at the following time points: pre-treatment (T0), predicted treatment (virtual setup) (TS), and post-treatment (T1). Both T0 and T1 were obtained from an intraoral scan (iTero® Element™, Align Technology).

For measurements of tooth movement, the eModel 9.0 Compare software (GeoDigm Corporation, Falcon Heights, MN, USA) was used to superimpose the digital models. This employed an automatic surface-to-surface closest point registration algorithm (iterative closest point) using the method previously described by Grünheid et al.[10] and Adel et al.[20] (Figure 3). This involved the following steps: (1) digital model registration, (2) generation of a coordinate system, and (3) measurement of tooth movement.

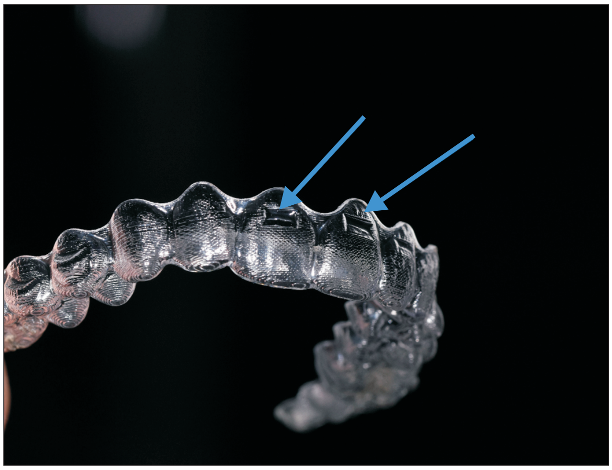

Figure 1. Power Ridges® feature (arrows) in Invisalign® clear aligners.

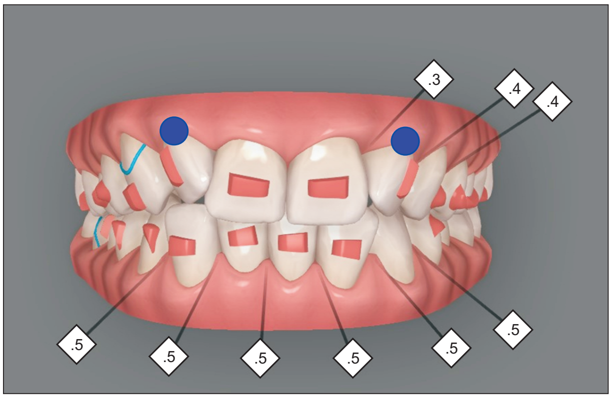

Figure 2. Horizontal rectangular attachments placed on the center of the labial surface of maxillary central incisors (4 mm long, 2 mm wide, and 1 mm thick).

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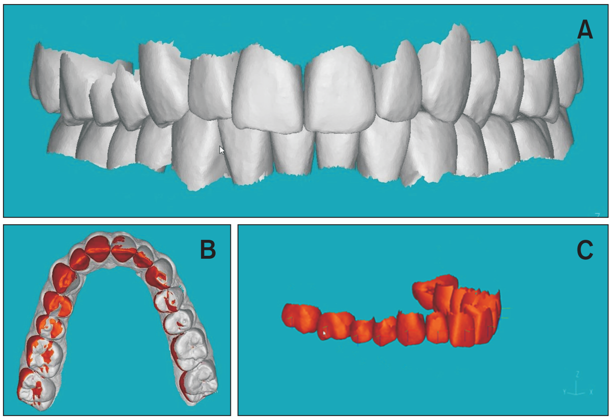

Figure 3. Tooth measurements performed on digital models using the "Compare" software. **A**, Segmentation of the digital models (TS and T1). **B**, Best-fit surface registration algorithm automatically superimposes individual teeth from the segmented models (TS or T1) on the corresponding teeth in the unsegmented T0 model. **C**, Local tooth reference frame that the software automatically generates, defining the principal local coordinate tooth axes being generated (Automated Tooth Coordinates).

Registration

The first step was to segment the digital models for the predicted treatment (virtual setup at TS) and the post-treatment model at T1. This separated each tooth into an individual object, which could then be compared with the digital pretreatment model at T0 (unsegmented)[20] (Figure 3). This was followed by a global initial alignment. The average occlusal plane (drawn from the mesiobuccal cusp tips of the maxillary first molars and the contact point between the central incisors) was used for initial registration. This was refined by 50 iterations of a closest point algorithm to achieve the best fit of the occlusal surfaces according to Grünheid et al.[10] Individual teeth from the segmented models (TS and T1) were then superimposed on the corresponding teeth in the pre-treatment unsegmented model with the best-fit surface registration.

Coordinate system generation

Reference frames were used to establish a coordinate system for measuring the tooth movements. This consisted of three perpendicular axes, the "x-axis" as the intersection of the sagittal and occlusal planes, the "y-axis" as the intersection of the sagittal and coronal planes, and the "z-axis" as the intersection of the coronal and occlusal planes. The origin of the coordinate system was established at the center of the clinical crown of the maxillary central incisor. For each tooth, the x-, y-, and z-axes indicate the mesiodistal, buccolingual, and occlusogingival directions, respectively. These axes were automatically created using a software based on the point cloud generated for each tooth (its geometric shape). Using well-established algorithms, the software creates an analogy of the tooth roots based on the point cloud and autogenerates the long axis of the teeth. Coordinates were generated using the software in the TS model, and analogous axes were created for each corresponding tooth in the T1 model.

Measurement of tooth movement

The third step involved the actual measurement of tooth movement. This was achieved by orienting all three digital models (T0, TS, and T1) using the same coordinate system, followed by an assessment of changes in tooth position. The predicted tooth movements were measured as the change in tooth position between the initial and setup models (TS and T0), whereas the actual achieved tooth movements were assessed from the change in tooth position between the initial and final models (T0 and T1). The angle between the reference plane and the virtual long axis of the tooth was measured. The change in the angular movement of each central incisor as it rotated around the x-axis was measured in degrees and recorded in Excel (Microsoft Excel 2016, Microsoft, Redmond, WA, USA) for comparison.

All the measurements were performed by the primary investigator. To determine the intra-examiner reliability, 10 random cases were measured again 2 weeks later. Dahlberg errors and concordance correlation coefficients (CCCs) were measured.[21,22]

Statistical analyses

Statistical analyses were performed using the SPSS software (version 20; IBM, Armonk, NY, USA). Correlations between the predicted and achieved labiolingual inclinations were calculated using CCCs. The Shapiro–Wilk test of normality was used to test the normality of all quantitative variables. Data were found to be normally distributed, and a paired-sample t test was used to compare the predicted and obtained data. Statistical significance was set at $P < 0.05$.

RESULTS

The mean age, treatment duration, and number of aligners per arch in both groups are shown in Table 1. Five of the 36 patients screened were noncompliant (13.9% of the initially screened patients). High intra-examiner reliability was observed (0.992–1.000), and the Dahlberg error ranged from 0.01 to 0.06.

Table 2 shows a comparison of the mean absolute differences in the predicted and achieved labiolingual inclinations between the Power Ridges® and attachment groups. The mean accuracies for the central incisors were

68.3% for the Power Ridges® and 71.6% for the attachments. There were no statistically significant differences between the two groups. The CCCs for the predicted and achieved inclinations were 0.66 and 0.67 for the Power Ridges® and attachment groups, respectively (Table 3). In addition, there was a low positive correlation between predicted inclination change and the average absolute difference between predicted and achieved inclinations (r = 0.19; 95% confidence interval, 0.08–0.30).

DISCUSSION

Adequate labiolingual inclination of the maxillary incisors in Class II division 2 malocclusions is crucial for achieving a good inter-incisal angle, adequate incisor contact, and sagittal correction of the dentition.[23] Our findings showed that the mean accuracies of achieving the predicted inclination for the maxillary incisors were 68.3% and 71.6% in the Power Ridges® and attachments groups, respectively. The average differences between the predicted and achieved inclinations were 4.51 ± 2.75° in the Power Ridges® group and 3.74 ± 3.17° in the attachments group (Table 2). Statistical comparison of the mean absolute difference between the predicted and achieved inclinations revealed no significant difference between the two groups.

Simon et al.[9] reported that Power Ridges® achieved a similar mean accuracy to attachments in determining palatal root torque. The mean accuracy for maxillary incisor torque was 42%. Conversely, Sandhya et al.[24] reported that horizontal ellipsoid attachments produced better root movements than Power Ridges®. These results were derived from finite element models rather than actual intraoral movements. Castroflorio et al.[25] found no significant differences between the virtual and actual measurements for torque corrections of approximately 10° using Power Ridges®. Nevertheless, they had a small sample size of six consecutive patients.

A recent systematic review concluded that the use of auxiliaries, such as Power Ridges® and attachments, could enhance the predictability of torque movement of the anterior teeth.[8] However, in that review, only a few studies were included in relation to anterior tooth torque movement, which had several limitations. This review also concluded that the use of Power Ridges® or attachments was insufficient to produce the correct amount of root control. This was confirmed by our results, in which approximately one-third of the predicted change in the inclination was not achieved. One explanation for this may be that aligners tend to lift during torquing, affecting the fit of the incisal part of the appliance with the

Table 1. The mean age, duration of treatment, and mean number of aligners per arch for both groups

	Group 1 "Power Ridges®"	Group 2 "Attachments"
Age (yr)	25.81 ± 2.97	26.88 ± 3.52
Duration of treatment (mo)	19.13 ± 6.24	17.16 ± 4.85
Mean number of aligners	32.29 ± 10.54	29.81 ± 14.22
Amount of crowding (mm)	3.37 ± 1.76	4.02 ± 2.50
Cephalometric measurements at T0		
SNA (°)	82.82 ± 2.98	84.68 ± 3.92
SNB (°)	77.97 ± 2.01	78.73 ± 1.43
ANB (°)	5.58 ± 1.28	6.15 ± 0.95
UI/SN (°)	102.33 ± 2.33	101.52 ± 2.93
LI/MP (°)	95.49 ± 4.74	94.11 ± 5.98

Values are presented as mean ± standard deviation.
UI/SN, upper incisor inclination to SN plane; LI/MP, lower incisor inclination to mandibular plane.

Table 3. Concordance correlation coefficient (CCC) for predicted and achieved inclinations using Power Ridges® and attachments

	CCC value	95% confidence limit	
		Lower limit	Upper limit
Group I (Power Ridges®)	0.66	0.44	0.80
Group II (Attachments)	0.67	0.43	0.83

Table 2. Comparison of the mean absolute difference of predicted and achieved labiolingual inclinations between the Power Ridges® and attachments groups

Tooth	Power Ridges®					Attachments					*P* value
	Mean predicted (SD)	Mean achieved (SD)	Mean difference (SD)	95% confidence interval		Mean predicted (SD)	Mean achieved (SD)	Mean difference (SD)	95% confidence interval		
				Lower	Upper				Lower	Upper	
Central incisor	11.91 (6.23)	7.81 (5.34)	4.51 (2.75)	3.41	5.61	10.21 (6.24)	7.25 (5.22)	3.74 (3.17)	2.47	5.01	0.4893

SD, standard deviation.

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tooth.[16] Hence, the force couple produced would not be sufficient and consequently lead to a lower efficiency of torque movements. Distortion of the appliance may also cause unintended intrusion of the teeth "watermelon seed effect."[26] Power Ridges® were introduced to reinforce the cervical area of the aligner and improve torque control. Simon et al.[27] reported significant torque compensation (7.9 N-mm) applied by aligners with Power Ridges® during torque movement of maxillary central incisors. In addition, a finite element study showed that Power Ridges® caused aligners to undergo distortion, generating an angle between the inner face of the aligner and the tooth surface, thereby favoring a counter moment.[28]

The CCCs for predicted and achieved inclinations were 0.66 and 0.67 for the maxillary central incisor Power Ridges® and attachments groups, respectively. This indicates a moderate correlation in both groups. Notably, in our sample, all central incisors were initially retroclined. This would be clinically significant in Class II division 2 malocclusion cases presenting with retroclined incisors, as the predictability of torque expression and achievement of the desired incisor inclination using clear aligners are likely to be reduced.

Torque movement is challenging in clinical orthodontics. With fixed the preadjusted appliances, torsional play between the archwire and the slot often results and is influenced by many factors, including the stiffness of the wire, wire size, manufacturer tolerance of the edge bevel and bracket slot size, play of the wire in the slot, bracket positioning as related to the morphology of the labial surface, and initial inclination of the tooth.[3] According to Archambault et al.,[3] torsional play or engagement angle in a 0.018-inch bracket slot varied from 31° when using a 0.016 × 0.016-inch archwire to 4.6° with a 0.018 × 0.025-inch archwire. For the 0.022-inch bracket slot, play varied from 18° with a 0.018 × 0.025-inch archwire to 6° with a 0.021 × 0.025-inch archwire. Different approaches are used to enhance torque prescription using fixed appliances, including altering bracket prescription and the use of full-dimension archwires to minimize torsional play. In the present study, the average differences between predicted and achieved inclinations were $4.51 \pm 2.75°$ in the Power Ridges® group and $3.74 \pm 3.17°$ in the attachments group (Table 2). Accordingly, it can be argued that this was close to the torsional play in fixed appliances when using a working archwire in a preadjusted edgewise bracket. The predictability of torque movement can be enhanced by overcorrection, staging of tooth movements, and attachments.[19]

Limitations of the study

The current study has some limitations. The change in the labiolingual inclination of the incisors can be due to different types of tooth movements, such as uncontrolled tipping, controlled tipping, or torque. The methodology used in the present study did not differentiate between the aforementioned types of tooth movement; rather, it measured changes using an algorithm vector construction of the incisor rotation around the x-axis, resulting in a change in the labiolingual inclination of the tooth. Further studies to differentiate the exact tooth movements that achieved a change in the labiolingual inclination are of great value. In addition, a prospective study design may provide a more comprehensive understanding of the factors influencing the outcomes we examined in this study.

CONCLUSIONS

Predicted inclination change is not fully achieved with Invisalign® clear aligners in both the Power Ridges® and attachments groups. Overcorrection of required tooth movements is thus recommended to achieve the required inclination change.

The mean accuracies of the achieved inclination movement for the central incisors are 68.3% for the Power Ridges® group and 71.6% for the attachment groups, with no significant differences between the groups.

AUTHOR CONTRIBUTIONS

Conceptualization: MS, AMH. Formal analysis: MS, AMH. Investigation: MAS, MS. Methodology: MS, AMH. Project administration: MAS. Resources: MS. Software: MAS. Supervision: MS, AMH. Writing–original draft: MAS. Writing–review & editing: MS, AMH.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

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