Original Article

Comparison of labio-palatal incisor movement between two wear protocols: a retrospective cohort study

Max Wei[a]; Tony Weir[b]; Brett Kerr[c]; Elissa Freer[d]

ABSTRACT

Objectives: To investigate the accuracy of the Invisalign appliance in achieving predicted angular tooth movement of the maxillary central incisors, to locate the center of rotation in a labio-palatal direction, and to investigate any difference between 1-weekly and 2-weekly wear protocols.

Materials and Methods: This study involved a retrospective sample of two groups of 46 Class I adult subjects treated non-extraction with different protocols of 1-weekly and 2-weekly wear. The pretreatment, predicted outcome and achieved outcome digital models were superimposed and measured using metrology software. Angular and center-of-rotation measurements in the sagittal plane for the maxillary right central incisor were analyzed.

Results: There was a statistically significant difference between predicted and achieved angular measurements ($P < .005$) for labial tooth movements regardless of wear protocol. For palatal movements, no statistically significant difference was observed ($P > .05$). A small amount of overexpression was observed in some cases. Regarding crown and root control, uncontrolled tipping was the most predictable. No statistically significant difference was found between predicted and achieved center of rotation, but the confidence interval was wide. No statistically significant difference ($P > .05$) was found between the two wear protocols for the parameters measured.

Conclusions: For maxillary central incisors, labial angular movements were not as accurate as palatal movements. Overcorrection could be recommended with careful clinical monitoring due to the possibility of overexpression. Control of root movements may be unpredictable, and further research is required to draw stronger conclusions. For the parameters measured in this clinical sample, there was no difference between the two wear protocols. (*Angle Orthod*. 2024;94:151–158.)

KEY WORDS: Clear aligner treatment; Labio-palatal movement; Center of rotation; Wear protocols

INTRODUCTION

Digital simulation and planning are integral to clear aligner treatment (CAT), and the use of metrology methods allows for comparison of predicted and post-treatment models, facilitating measurement of tooth movement.[1]

Recent literature has reported shortfalls in the ability of CAT to control maxillary central incisor torque.[2–7] Jiang et al.[8] found that palatal root movement was not as accurate as labial root movement. Gaddam et al.[5] found a similar trend and suggested some palatal movements could yield overexpression. Correct maxillary incisal torque is important for an optimized occlusion and smile arc.[9] If there is insufficient incisor labial crown torque, anterior premature contact may result, leading to posterior open bite.[5] Maxillary incisor inclination can also influence the arch length as well as the final interincisal angle, which may be important for stable deep-bite correction.[10,11]

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The center of rotation (CRo) of a tooth moved in the sagittal plane needs to be considered, as it affects the relative amounts of root and crown movement. Drake et al.[12] found CAT had a tendency to produce uncontrolled tipping of the root within their short study time of 8 weeks. Jiang et al.[8] reported similar results and concluded that root movements other than uncontrolled tipping remained largely unpredictable.

To this date, only a few studies have investigated aligner wear protocols.[13,14] To add to the current literature in relation to an appropriate wear protocol and its influence on maxillary central incisor movement in the labio-palatal direction, the present study had the following objectives:

1. To investigate the accuracy of the Invisalign appliance (Align Technology, Tempe, Ariz) in achieving predicted angular tooth movements in a labio-palatal direction
2. To investigate the ability of CAT to achieve the predicted CRo in the labio-palatal direction
3. To investigate whether there is a difference between 1-weekly wear (1WW) and 2-weekly wear (2WW) protocols in achieving predicted angular movement and CRo.

For the first two objectives, the null hypothesis was that there would be no difference between the measured predicted and achieved parameters. For the third objective, the null hypothesis was that there would be no difference between the two wear protocols in achieving predicted angular movement and CRo.

MATERIALS AND METHODS

The University of Queensland Research Ethics and Integrity Office reviewed and granted ethics exemption for this retrospective study (ID: 2021/HE001935). The data originated from Australasian Aligner Research Database, which has been contributed to by more than 10 orthodontists from Australia, New Zealand, and the United States who have at least 10 years of experience with CAT.

Initial sampling divided the cases by 1WW and 2WW protocols, and they were randomized in order. The first 46 cases were selected consecutively if they met the inclusion criteria as outlined in Table 1. The maxillary arches were exported as stereolithography files for three instances: pretreatment stage (T1), predicted treatment outcome (T2), and achieved treatment outcome (T3).

The maxillary arches were imported into Geomagic Control X (3D Systems, Rock Hill, SC) for superimposition, using a technique involving best-fit alignment with 50 iterations.[2,14–17] The T1 and T2 models were superimposed for analysis of programmed movement (Figure 1A). The T1 and T3 models were superimposed for measurement of treatment-induced movement (Figure 1B).

Table 1. Inclusion and Exclusion Criteria of the Sample

Inclusion criteria
- Treatment with Invisalign
- Completion of treatment (initial set of aligners)
- Stereolithography files present at T1, T2, and T3
- Adult patients (age >18 y)
- Nonextraction treatment
- Class I malocclusion
- No use of intermaxillary elastics
- Maxillary central incisors with no attachments and no interproximal reduction

Exclusion criteria
- Systemic disease that can affect tooth movement
- Pharmacologic treatment that can affect tooth movement
- Congenitally missing teeth (other than third molars)
- Periodontal disease

After superimposition, the maxillary right central incisor on the T1 model was selected for the software to construct a vector through the geometric center of the tooth (Figure 2A). This was reproduced on the T2 model. A sagittal plane, slicing through the T1 vector, was constructed perpendicular to an automatically generated coronal plane (Figure 2B,C). The T2 vector was projected onto the sagittal plane (Figure 2D). The angle between the two vectors on the same plane was measured in degrees (°) and represented the programmed or predicted angular movement (Figure 2E). The intersection of the vectors marked the location of the predicted CRo, and the distance to the incisal edge was recorded in millimeters. This was repeated for T1 and T3 superimposition to measure the achieved angular movement and CRo.

To qualify the type of root movement, the CRo was compared with the theoretical center of resistance (CRe). The CRe was estimated to be one-third of the root length from the alveolar bone crest, similar to the cemento-enamel junction in patients without periodontal disease.[18,19] The average length of the crown and root of a maxillary central incisor was estimated using population means.[20] Based on the distance between CRo and CRe, the types of root movement were qualified (Figure 3), as guided by the current literature.[8,17]

A power calculation was conducted with a pilot study of 10 patients for paired-samples *t*-test for the angular measurement method described. A total sample of 38 cases per wear protocol was required for a mean difference of 2.27 ± 4.88 to achieve a statistical 80% power at 5% significance level. The total sample for each wear protocol was increased to

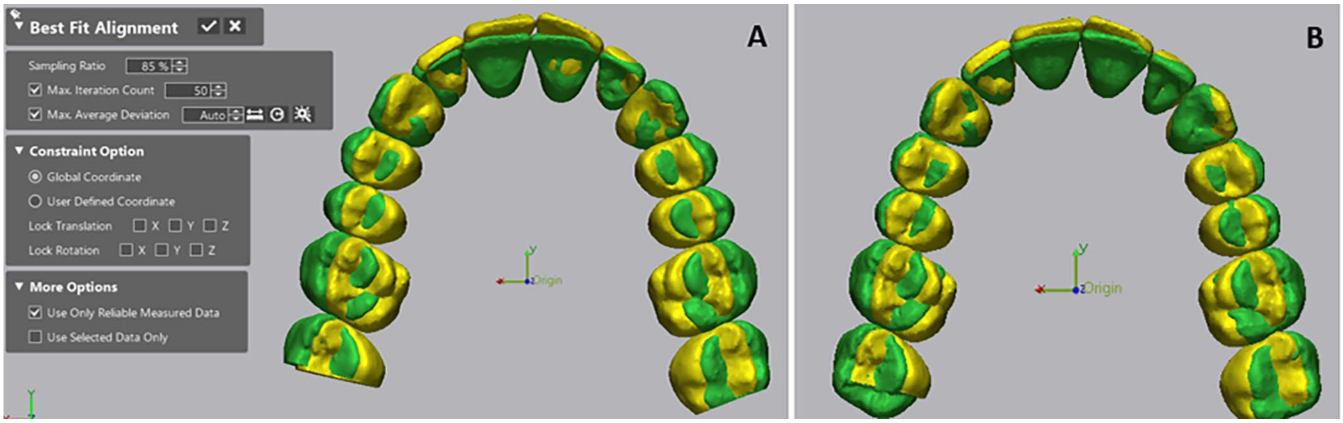

Figure 1. Superimposition of models. (A) Superimposition of T1 and T2 models. T1: yellow, T2: green. (B) Superimposition of T1 and T3 models. T1: yellow, T3: green.

46 to increase power. Statistical management and analysis were conducted with Excel (Microsoft, Redmond, Wash) and SPSS (IBM, Armonk, NY). Intrarater and interrater reliability were assessed by intraclass correlation coefficient (ICC). Intrarater reliability was conducted by measuring the data of 10 subjects on two occasions, 2 weeks apart, by the same examiner (Dr Wei). Interrater reliability was assessed from the results measured from the same data by two examiners (Dr Wei, Dr Anand). The ICC was perfect, which was expected since the vectors and planes were generated by software algorithms.

Paired-samples *t*-test and Wilcoxon signed-rank test were used, in accordance with the Shapiro-Wilk normality test results to compare the predicted values and achieved values for angular and CRo measurements. To compare the angular and CRo deviations between the wear protocol groups, the Mann-Whitney *U*-test was conducted with confidence intervals (CIs) estimated by the Hodges-Lehmann method.

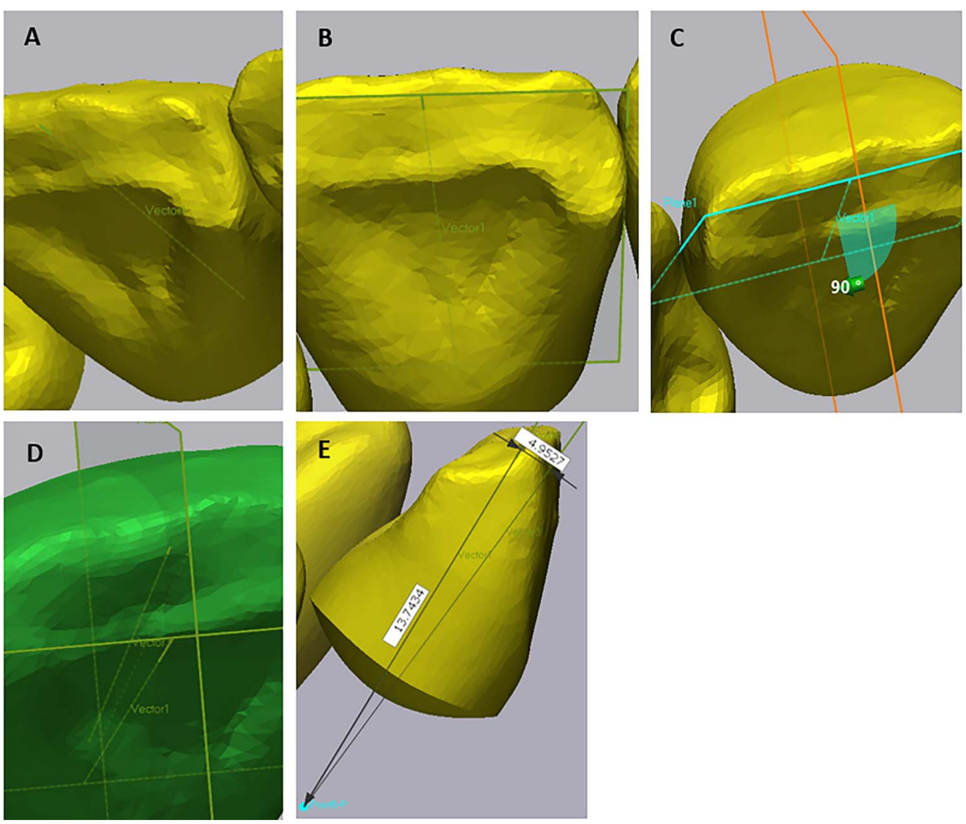

Figure 2. Construction of vectors and planes for angular and center-of-rotation measurements.

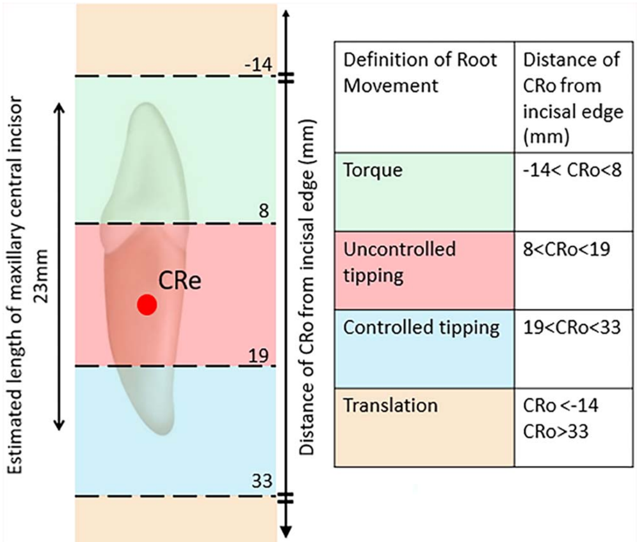

Figure 3. Qualification of root movement according to position of center of rotation.

RESULTS

Angular measurements for the sample are presented in Table 2 and Figure 4. Four teeth moved in the opposite direction to those planned and were removed from further analysis. Descriptive statistics for the predicted and achieved angular values for the groups analyzed are presented in Tables 3 and 4. Accuracy in percentage (%) was calculated from the equation: (achieved value/predicted value) $\times$ 100%, with values derived from mean averages.

The results of the paired-samples *t*-test and Wilcoxon signed-rank test are presented in Table 5. The groups were sorted by wear protocol and the direction of movement. For 1WW palatal and 2WW palatal groups, there was no statistically significant difference between predicted and achieved values ($P = .203$, $P = .823$). Statistically significant differences between the predicted and achieved values were found for both 1WW and 2WW labial movement groups ($P = .002$, $P < .001$).

Because a significant proportion of the cases had overexpression of planned movement, the paired equivalence tests were repeated for the sample grouped by wear protocol and type of expression (Table 5). The CI reported was narrower for the overexpression groups than for the underexpression groups.

The Mann-Whitney *U*-test was conducted to compare the two wear protocols, and no statistically significant difference was found for any of the comparison groups (Table 6).

There were unequal numbers of cases across the four documented categories of root movement (Table 7). For 1WW uncontrolled tipping cases, 77% resulted in the same movement type. For 1WW torque movements, 67% of the cases had conformity. For 2WW uncontrolled tipping cases, 72% resulted in the same movement type. For 2WW torque cases, only 33% resulted in the same movement type.

The Wilcoxon signed-rank test showed that there was no statistically significant difference between the achieved CRo and predicted CRo for the groups sorted by wear protocol and direction of movement (Table 8). The CIs were wide, especially for the palatal groups. The Mann-Whitney *U*-test (Table 9) showed that there was no statistically significant difference between the CRo deviation of 1WW cases and 2WW cases ($P = .151$).

DISCUSSION

One of the aims of this study was to investigate the accuracy of CAT in achieving predicted angular tooth movement in a labio-palatal direction. The paired-samples tests of equivalence showed that, for the palatal crown movement cases of the two wear protocol groups, there was no statistically significant difference between the predicted and achieved values. On the other hand, statistically significant differences between the predicted and achieved values were found for labial crown movement cases of both wear protocol groups. The CI was also in the negative range, suggesting a tendency of underexpression in these labially directed cases. The current study found a mean accuracy between 55% and 58% for labially directed cases, which was comparable with that of the current literature.[2,4,8]

The trend that labial crown movement was less accurate than palatal movement was also consistent with the literature.[3,5,8] However, the non–statistically significant difference for palatal movements was not reported by those studies. This could have been due to

Table 2. Number of Cases (n) in Each Group (Wear Protocol/Direction of Movement) and Types of Expression

	Underexpression, n	Overexpression, n	Wrong Direction, n	Total, n
1WW/labial	19	7	1	27
1WW/palatal	11	7	1	19
1WW total	30	14	2	46
2WW/labial	19	5	1	25
2WW/palatal	9	11	1	21
2WW total	28	16	2	46

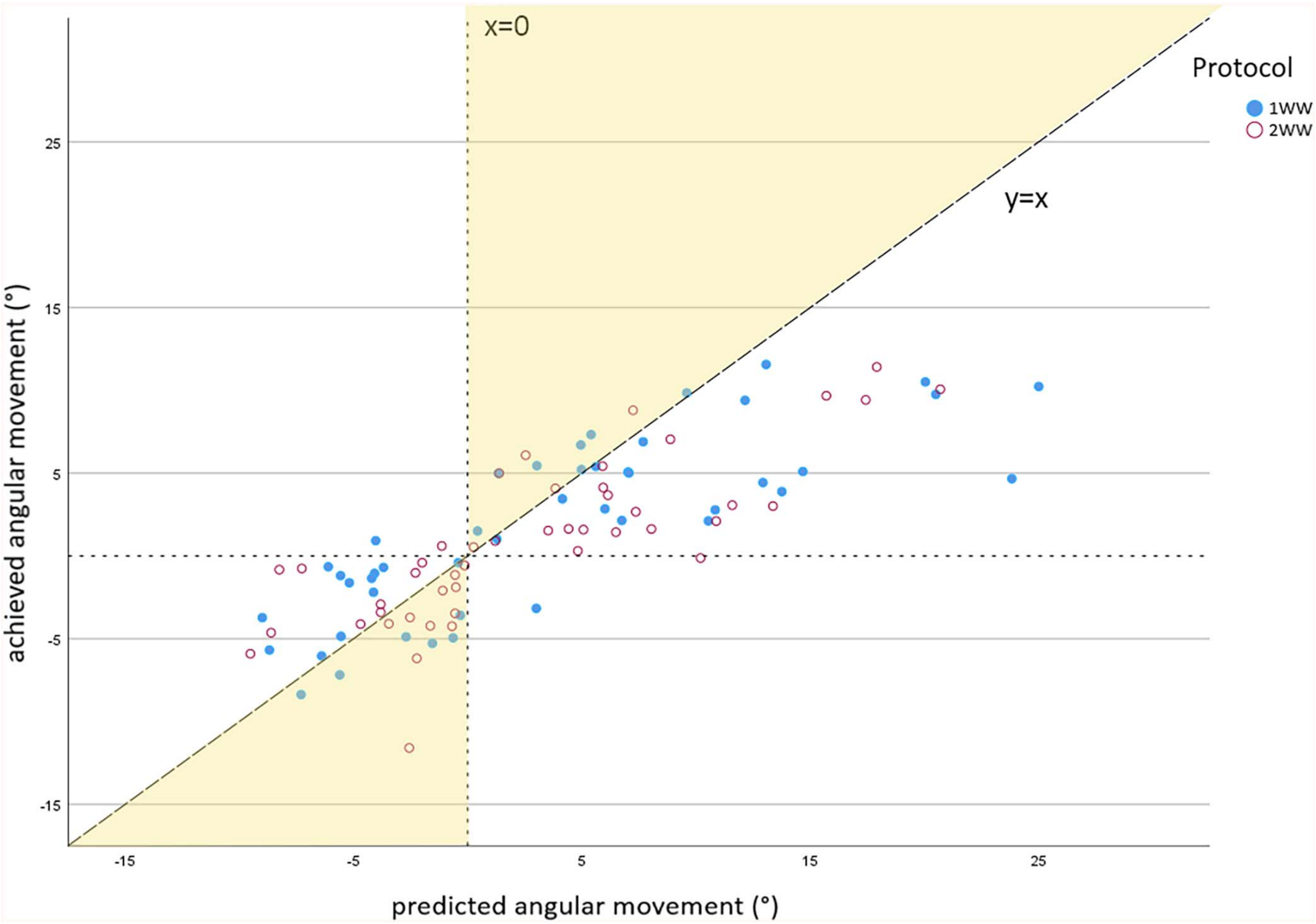

Figure 4. Predicted angular movement values vs achieved angular movement values of the studied cases. Shaded area: overexpression.

Table 3. Descriptive Statistics for Protocol/Direction Groups

		Predicted Values, °					Achieved Values, °					
Group	n	Mean	Median	Max	Min	IQR	Mean	Median	Max	Min	IQR	%
1WW/labial	26	9.72	7.37	25.01	0.43	8.27	5.67	5.09	11.57	1.02	4.55	58
2WW/labial	24	7.94	6.31	20.69	0.26	7.43	4.38	3.67	11.41	0.31	5.21	55
1WW/palatal[a]	18	4.51	4.70	9.00	0.33	3.77	3.54	3.66	8.37	0.41	4.22	78
2WW/palatal[a]	20	3.31	2.41	9.52	0.14	3.68	3.36	3.43	11.59	0.41	3.19	102

[a] Absolute value applied to palatal movement cases to yield positive values.

Table 4. Descriptive Statistics for Protocol/Expression Groups

		Predicted Values, °					Achieved Values, °					
Group	n	Mean	Median	Max	Min	IQR	Mean	Median	Max	Min	IQR	%
1WW/overexpression	14	3.45	2.87	9.59	0.33	4.86	5.41	5.25	9.85	0.41	2.66	157
2WW/overexpression	16	1.95	1.51	7.24	0.14	2.00	4.23	4.09	11.59	0.54	3.88	217
1WW/underexpression	30	9.52	7.04	25.01	1.29	7.51	4.51	4.16	11.57	0.65	3.78	47
2WW/underexpression	28	8.06	6.88	20.70	1.21	6.06	3.74	2.96	11.41	0.31	3.77	46

different sample characteristics. Smaller palatal movements could have produced more accurate results, as suggested by Castroflorio et al.[21] It has been suggested in the literature that the buccal bone has less resistance than that of the palatal, so labial root movement (palatal crown movement) might have more accuracy.[8]

The presence of the overexpression of crown movement is scarcely reported in the literature.[5,17,22] The

Table 5. Paired-Sample Equivalence Test Comparing Predicted and Achieved Movement by Group

Group	n	Test Done	95% Confidence Interval of the Difference		*P* Value
			Lower	Upper	
1WW/labial	26	Paired-sample *t*-test	−6.392	−1.708	.002
2WW/labial	24	Wilcoxon signed-rank test	−5.388	−1.634	< .001
1WW/palatal	18	Paired-sample *t*-test	−2.513	0.575	.203
2WW/palatal	20	Wilcoxon signed-rank test	−1.585	1.587	.823
1WW/overexpression	14	Paired-sample *t*-test	1.16	2.76	< .001
2WW/overexpression	16	Wilcoxon signed-rank test	0.982	3.230	< .001
1WW/underexpression	30	Wilcoxon signed-rank test	−6.288	−2.759	< .001
2WW/underexpression	28	Wilcoxon signed-rank test	−5.545	−2.795	< .001

Table 6. Mann-Whitney *U*-Test for Various Comparison Groups

Group	n	95% CI (Hodges Lehman)		*P* Value
		Lower	Upper	
1WW/overexpression vs 2WW/overexpression	14 16	−1.319	1.110	1
1WW/underexpression vs 2WW/underexpression	30 28	−1.919	1.564	.852
1WW/labial/underexpression vs 2WW/labial/underexpression	19 19	−3.839	1.977	.795

Table 7. Conformity in Type of Root Movement

Change Protocol	Torque	Uncontrolled Tipping	Controlled Tipping	Translation
1WW, % (n)	67 (15)	77 (22)	50 (2)	20 (5)
2WW, % (n)	33 (12)	72 (18)	0 (3)	27 (11)

limited report of this could be a product of different mathematical calculations. Interestingly, 30% of the cases in the 1WW group and 35% in the 2WW group had overexpression, so further investigation into these cases was conducted. Table 5 showed expected statistically significant differences for all groups, and a further examination of the CIs was essential. For the overexpression groups, the CIs were narrower, and the mean and median differences between the achieved and predicted values were less than that of the underexpression groups. This may suggest that overexpression could occur in small amounts in some cases, which was consistent with that reported by Gaddam et al.[5]

Overexpressed movements could be a clinical issue, even though the present study showed this may manifest in only small amounts. As this can happen in both labial and palatal movements (23% and 63% of the cases, respectively), careful clinical supervision is required. This is even more pertinent if overcorrection is planned, especially for expected underexpressed labial movements. Overcorrection may be planned as the sole movement for the last few aligners with judicious preemptive review to determine if those additional aligners would need to be prescribed. Careful clinical supervision would also be crucial to detect the cases that had moved in the opposite direction to that predicted. This small, but potentially significant (4.3% of total cases), amount of "randomness" was also reported in the literature.[5,17,22]

Table 8. Results of Wilcoxon Signed-Rank Test Results for CRo Deviation With Groups Split by Wear Protocol/Direction of Movement

Group (Protocol/Direction)	n	*P* Value	95% Confidence Interval	
			Lower	Upper
1WW/labial	26	.603	−2.123	3.511
2WW/labial	24	.116	−0.650	7.242
1WW/palatal	18	.879	−6.954	22.134
2WW/palatal	20	.296	−7.395	32.638

Table 9. Mann-Whitney *U*-Test Results for Center of Rotation Deviation by Wear Protocol

Comparison Group	n	95% Confidence Interval (Hodges Lehman)		*P* Value
		Lower	Upper	
1-weekly vs 2-weekly	44 44	−8.216	1.744	.151

Overexpression could be due to the following: (1) the "bow-string" effect, in which failed expansion or constriction in the posterior region allowed for distortion of the aligner in the anterior region, thus producing exaggerated labial or palatal movements, respectively[5]; (2) the failure of nearby teeth to align and allow space for movement; and (3) the underestimation of the size of some of the anterior teeth, leading to a tighter fit, resulting in a misdirection of intended force.[23] These circumstances may have also led to the "randomness" reported; however, further research would be required to confirm these speculations.

Across all groups examined, there was no statistically significant difference between the two wear protocols. This statistical finding was similar to that of the current limited literature.[13,14] This finding had to be considered with the current sample involving adult patients treated without extractions and without the use of intermaxillary auxiliaries and had Class I molar classification, which was similar to that described by Al-Nadawi et al.[14] The pretreatment Peer Assessment Rating (PAR) score of the sample described by Clements et al.[13] suggested that their cases could be of mild to moderate difficulty. Conclusions applicable to more difficult cases would require further research.

The results showed that cases with programmed uncontrolled tipping had the highest percentage of conformity in achieving the same type of root control, which was consistent with that suggested by Jiang et al.[8] The Wilcoxon signed-rank test showed no statistically significant findings. However, the *P* values must be interpreted with caution, as the matching CIs were wide. The upper boundary was broader than the lower, which may suggest a tendency for the CRo to move toward the apex of the tooth, especially for palatal movements. However, this would require further research with greater numbers in specific root movement subgroups to draw a stronger conclusion.

To compare the efficacy of the wear protocols in achieving the predicted CRo, the Mann-Whitney *U*-test was conducted, and no statistically significant difference was found. It was difficult to compare this finding to that of the literature as there have been no previous investigations involving both root control and wear protocols. It would be expected that 2WW should express better root control according to the theory that root movement involving larger surface areas may require longer duration for force application and biological changes.[24,25] However, the current results on both angular movement and CRo did not indicate this. This may suggest that, for mild to moderate difficulty cases, there was no advantage to lengthening the wear time between each aligner, so that the application of the 1WW protocol may reduce treatment time.

Being retrospective in nature, this study was subject to selection bias, and efforts were made to reduce this. The database required the contributing clinicians to submit all their cases to avoid selection of specific cases. To limit the issue of clinicians assigning their cases to a particular wear protocol based on their perception of the difficulty, the selection criteria were implemented to produce a homogenous sample. By using pre- and posttreatment scans, this study may have excluded those cases not requiring refinements. The clinicians' treatment protocols and patient compliance level were not available from the database. Adult patients were selected to reduce the influences of growth and bony characteristics on the treatment outcome and tooth movement rates. Fully erupted teeth in adults provide better contact for aligner material to deliver forces and longer moment arms.

As previously discussed, staging and the expression of other tooth movements may have influenced the expression of the variables measured. Unfortunately, in a clinical situation, it was impossible to limit all other movements. Even though all selected cases had no attachments on the central incisors, the presence of attachments on other teeth were not standardized. As all measurements were based on intraoral scans, the anatomy of the roots were not available for analysis in relation to the type of root movement control. The use of best-fit alignment superimposition has been popularly used in the literature even though its accuracy has not yet been rigorously investigated.[2,4,5,14–17] Adel et al.[26,27] explored the accuracy of this superimposition technique and found good accuracy, although that conclusion was limited to the magnitude of movements tested. More research into this area would allow refinement of metrology methods.

CONCLUSIONS

- Labial angular movements were less accurate than palatal movements. Some cases experienced overexpression, although this may not be clinically significant. To account for clinical shortfalls, overcorrection could be recommended, but careful clinical monitoring would be crucial; otherwise, further correction is required in the refinement stage.
- Programmed uncontrolled tipping may be the most accurately reproduced root movement. There was a tendency for the achieved center of rotation to move toward the apex in comparison to that predicted. However, further research with cases specifically selected for various center of rotations would be required to draw stronger conclusions.
- The results regarding angular measurements and center of rotation showed that there was no difference between 1-weekly wear and 2-weekly wear protocols. The application of the current findings to

other tooth movements and other sample characteristics would not be practical.

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