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Efficacy of Invisalign attachments: A retrospective study

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Introduction: The purpose of this study was to compare the efficacy of Invisalign's (Align Technology, Santa Clara, Calif) optimized and conventional attachments on rotational and extrusive tooth movements. **Methods:** Initial, predicted, and achieved digital dental models from 100 orthodontic patients were exported from Invisalign's ClinCheck software as stereolithography files and subsequently imported into the Slicer CMF program (version 4.7.0; http://www.slicer.org) for superimpositions on posterior teeth with no planned movement. Rotational and extrusive measurements for both optimized and conventional attachments were made on 382 teeth from the superimposition of the initial and predicted models (predicted movement) and from the superimposed initial and achieved models (achieved movement). Predicted and achieved movements were compared along with movements of teeth with optimized and conventional attachments. **Results:** Differences between accuracies of tooth movements using optimized vs conventional attachments for both rotation and extrusion were neither statistically nor clinically significant. Mean predicted values were larger than mean achieved values for all attachment types and movements ($P < 0.0001$). For extrusion, the mean difference between predicted and achieved movements was clinically significant (0.40 mm and 0.62 mm for optimized and conventional attachments, respectively). Overall, the mean accuracy was 57.2%. Mean accuracy was 63.2% for rotation and 47.6% for extrusion. Interproximal reduction or spacing did not significantly affect accuracy. **Conclusions:** Conventional attachment types may be just as effective as Invisalign's proprietary optimized attachments for rotations of canines and premolars and extrusion of incisors and canines. Clinicians should consider overcorrecting tooth movements, especially anterior tooth extrusion. (Am J Orthod Dentofacial Orthop 2021;160:250-8)

Although fixed orthodontic appliances are still widely used today, the advent of removable clear aligners has undoubtedly revolutionized the field of orthodontics in recent years. In 1997, Align Technology (Santa Clara, Calif) developed Invisalign, which is arguably the most used and recognizable clear aligner system today. Initially, each Invisalign aligner was programmed to move a tooth 0.25 to 0.33 mm over 14 days.[1,2] In 2016, Invisalign changed its protocol from two-week wear to weekly aligner switches, decreasing treatment time by up to 50%.[3] Each aligner is to be worn for 20-22 hours a day to be effective.[1,4]

Several studies have evaluated the accuracy of the Invisalign system by superimposing predicted and achieved virtual models over unmoved posterior teeth using 3-dimensional (3D) superimposition software.[2,5-10] Although it is possible that the teeth superimposed on may move during treatment, more stable landmarks (ie, palatal rugae) are not available on Invisalign's predicted models because they only illustrate teeth and attached gingiva. In addition, most of these studies were conducted before the release of Align Technology's SmartTrack (LD30; Align Technology) material developed in 2013 and before weekly aligner switches were recommended in 2016.

A recent systematic review concluded that Invisalign could predictably level, tip, and derotate anterior teeth, but not canines and premolars. The authors found that limitations of Invisalign also include posterior arch expansion through bodily tooth movement, closure of extraction spaces, improvement of occlusal contacts, extrusion of maxillary incisors, and correction of large

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anteroposterior and vertical discrepancies.[11] To increase effectiveness, composite attachments are bonded to teeth so that the aligner can be more retentive and to facilitate tooth movement.[12]

The first Invisalign attachments were conventional attachments that were either ellipsoid or rectangular in shape. The ellipsoid shape is considered the least effective attachment today because of its small size and lack of a defined active surface.[12] Conventional rectangular attachment dimensions, prominence, degree of beveling, and position on the tooth may be changed according to clinician preference in the ClinCheck Pro software (Align Technology) and are still widely used today. Optimized attachments, a type of SmartForce feature introduced in 2009, are engineered and patented by Align Technology to create precise biomechanical forces on teeth, thus increasing the predictability of tooth movement.[12] They vary by shape and are automatically placed by the ClinCheck software when a certain amount and type of planned tooth movement is detected. Optimized rotation attachments are automatically placed onto canines or premolars when a rotation of $\geq 5^\circ$ is detected. Maximum rotational velocity is 2° per stage. Optimized extrusion attachments are applied on to incisors or canines when ≥ 0.5 mm extrusion is detected by the software. Maximum linear velocity is 0.25 mm per stage.[13]

Unlike optimized attachments, conventional attachments are not unique to Invisalign and are used by other companies offering clear aligners or software to create in-office aligners using 3D printers. Although the precision of orthodontic tooth movements with Invisalign has been studied, the effectiveness of the different attachment types, among other aligner variables, has not been considered. This research aimed to compare the efficacy of optimized and conventional attachment types on rotations of canines and premolars and extrusion of anterior teeth—two movements reported to be the most difficult to achieve predictably with Invisalign.[11] Results can help guide dentists in their choice of attachment types or in considering any overcorrection of movements when treatment planning with Invisalign or another clear aligner software.

MATERIAL AND METHODS

This retrospective study consisted of 382 teeth from digital dental models of 100 orthodontic patients aged 11-63 years (32 males and 68 females with a mean age of 28 years 2 months). The sample teeth were derived from 97 maxillary arches and 60 mandibular arches. Some patients were used more than once because they had a refinement scan available with qualifying teeth for a total of 120 subjects. All patients were treated with Invisalign (Align Technology) by 1 of 2 orthodontists in private practice outside of Milwaukee, Wis and Chicago, Ill between October 2016 and August 2018. Both orthodontists had been providing Invisalign for at least 5 years before when the patients were started. A power analysis indicated that a sample size of at least 64 teeth per group would be needed to have a power of 95% with a significance level (α) of 0.05. The number of attachment types were: 163 optimized rotation (43%), 72 conventional rotation (19%), 81 optimized extrusion (21%), and 66 conventional extrusion (17%). Aligners were changed once a week according to the manufacturer's and clinician's recommendations at the time. The average number of aligners per series was 20, corresponding to an average treatment time of 5 months. Spacing was present or interproximal reduction (IPR) performed on either side of 61 out of the 382 teeth studied (16%). The study protocol was approved by the Institutional Review Board of Marquette University.

The main inclusion criteria were as follows: (1) presence of optimized or conventional rotation or extrusion attachments in the planned ClinCheck; (2) completion of the initial series of aligners, resulting in either a refinement or final scan; (3) no planned movement of at least one posterior tooth per side of the dental arch; (4) good compliance reported with aligner wear; (5) full permanent dentition; and (6) treatment beginning in 2016 or later. The exclusion criteria were: (1) patients in the primary or mixed dentition; (2) new dental restorations or extractions during treatment; (3) the use of any auxiliaries, such as elastics or vibrational devices; and (4) patients with any orofacial syndromes or malformations.

To detect which teeth had conventional attachments placed primarily for rotation or extrusion, the previous unaccepted ClinChecks were reviewed to confirm that an optimized rotation or extrusion attachment was removed and replaced by a conventional one. Removal and replacement of an optimized attachment would indicate that conventional attachments were placed on teeth with planned rotations of $\geq 5^\circ$ or planned extrusion of ≥ 0.5 mm, which are the thresholds for optimized attachments to be placed. Predicted rotation was divided into mild ($<45^\circ$), moderate (45°-55°), or advanced ($>55^\circ$), whereas predicted extrusion was also divided into mild (<2.5 mm), moderate (2.5-3.5 mm), or advanced (>3.5 mm), according to Align Technology's classifications.[14]

Initial, predicted, and achieved digital dental models were exported from the ClinCheck software as stereolithography files. The initial and final models from the original ClinCheck were labeled as "initial" and "predicted," respectively. The models from the midtreatment refinement scan or the models from the final scan at the end of treatment (whichever came first) were labeled as "achieved." The stereolithography files were then imported into the 3D Slicer CMF program (version 4.7.0; http://www.slicer.org) for superimpositions and measurements. Fiducial markers were placed on the central pits of posterior teeth planned to have no movement, and a region of interest was selected to include the entire occlusal surface, at a minimum, to superimpose on. Gingival margins were not included as superimposition landmarks because the virtual gingiva in treatment simulations may be inaccurate and misleading. Initial and predicted models were superimposed to measure predicted tooth movements, whereas initial and achieved models were superimposed to measure achieved movements (Fig 1).[6]

Measurements were made on the teeth as follows: (1) for rotations of canines and premolars, two landmarks were manually placed on each tooth, the points were automatically connected to form a straight line, and the angle (yaw) between the two lines from each model was calculated by the software in degrees (°) (Fig 2). The landmarks used were usually buccal and lingual cusp tips on premolars or a cusp tip and cingulum on canines. If the cusp tips or cingula were ill-defined or the points not reproducible, the most mesial and distal points of each tooth were used; and (2) for extrusion of incisors and canines, one point was chosen near the center of the incisal edge or cusp tip of each tooth, and the vertical distance between the two points on each model was calculated in millimeters (mm) (Fig 3).

To account for any error in model superimposition because of inadvertent vertical movement of posterior teeth superimposed on, all achieved extrusive measurements were adjusted by comparing them to a control tooth. The control teeth were typically directly adjacent to those being measured so that they were roughly in the same anteroposterior position along the dental arch. Control teeth were measured to confirm no predicted vertical movement (0 ± 0.05 mm). If the movement was achieved even though no movement was predicted, it was assumed this was because of either intrusion or eruption of the teeth superimposed on. The achieved value from a control tooth was subtracted from the achieved value of the adjacent tooth of interest to calculate the true extrusion of the latter.

Statistical analysis

To calibrate the principal investigator to a uniform measuring method, all of the measurements were performed only after initially completing several measurements as a practice exercise. The same examiner repeated 40 of the rotational measurements and 40 of the extrusive measurements by random within a 3-week interval to assess intraexaminer reliability. The intraclass correlation coefficient was excellent, with a score of 0.970 (95% confidence interval [CI], 0.944-0.984) for overall mean difference values. For rotation, Cronbach's alpha was 0.965 (95% CI,

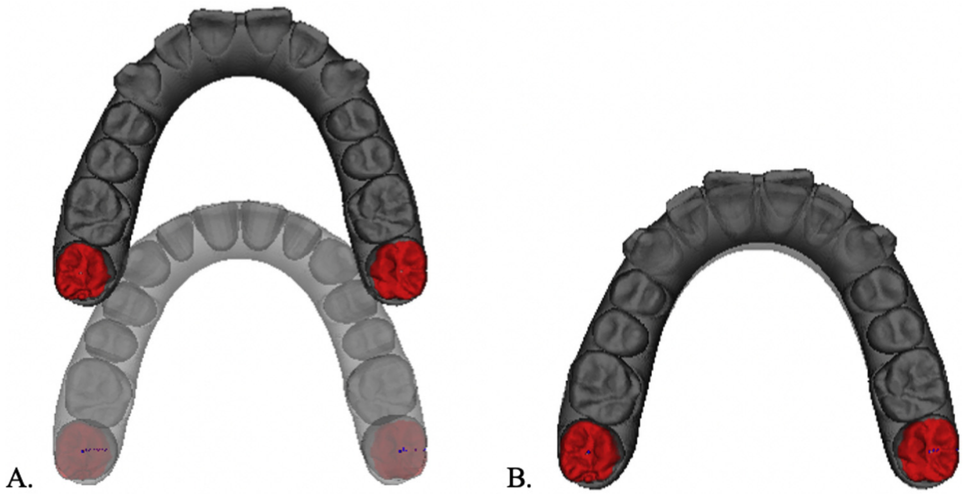

Fig 1. 3D model superimposition using 3D Slicer CMF: **A,** regions of interest on unmoved second molars of initial (*top*) and predicted (*bottom*) maxillary arches; **B,** arches after they were superimposed.

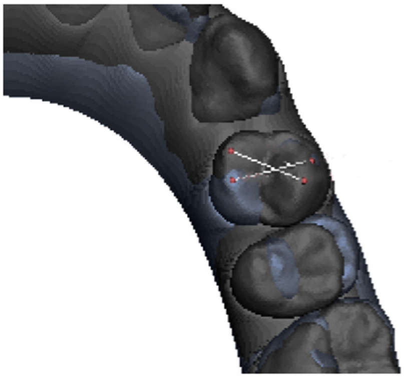

Fig 2. Rotational measurements.

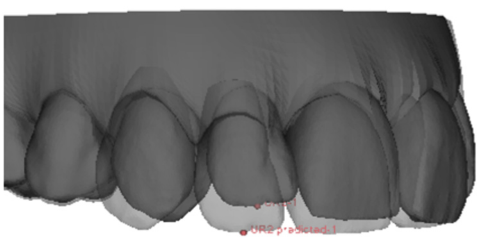

Fig 3. Extrusive measurements.

0.914-0.986). For extrusion, intrarater reliability had a value of 0.907 (95% CI, 0.780-0.962).

Any tooth measured to have a negative achieved value for a vertical movement, indicating intrusion, was changed to 0 mm because no extrusion was achieved. This was done to avoid large negative percentages when calculating accuracy (% accuracy = 100 − [(|predicted − achieved|)/(|predicted|) × 100]). In this equation, the absolute value of the difference between predicted and achieved movements was taken to ensure that percent accuracy never exceeded 100% for the teeth that achieved movements beyond what was predicted. To account for this same situation, the absolute value was also taken when calculating the discrepancy between predicted and achieved measurements in degrees and millimeters to avoid yielding negative values that would affect the mean without accounting for directionality.

To reduce the number of variables, similar types of teeth were grouped, including contralateral teeth, maxillary first and second premolars, mandibular first and second premolars, and mandibular central and lateral incisors. Independent *t* tests (two-tailed) were used to compare mean predicted and achieved movements between optimized and conventional attachments. Paired *t* tests (two-tailed) were used to compare mean predicted and mean achieved movements within groups. A one-way analysis of variance was used to compare the mean accuracies of movements among tooth types. Data analysis was performed using Statistical Analysis Software (version 9.4; SAS, Cary, NC) at a significance level of $P < 0.05$.

RESULTS

Descriptive statistics for both rotation and extrusion with optimized and conventional attachment types are presented in Tables I–IV. When comparing the efficacy of optimized and conventional attachments, the mean differences in raw values were higher for conventional attachments, and mean percent accuracies were higher for optimized attachments, but this did not reach statistical significance for both rotation and extrusion ($P > 0.05$) (Table V).

For all tooth movements and attachment types, mean predicted values were significantly larger than mean achieved values ($P < 0.0001$) (Table VI). Table VII shows mean accuracies by tooth type for both rotation and extrusion. The mean accuracy for all movements studied was 57.2%. The mean accuracy for rotation was 63.2%, whereas, for extrusion, it was 47.6%. The most severe planned movements for both rotation (74.0°) and extrusion (4.21 mm) had an accuracy of 64%. The least accurate tooth movement was mandibular canine extrusion with a conventional attachment (16.1%). The most accurate tooth movement was extrusion of the maxillary central incisor with a conventional attachment (73.9%), followed closely by rotation of the maxillary premolar with an optimized attachment (72.8%). Sixteen teeth were shown to intrude an average of 0.16 mm, so these achieved movements were changed to 0 mm for extrusion, yielding a 0% accuracy.

A one-way analysis of variance showed that there was no statistically significant difference between tooth types for rotation and extrusion when considering raw data measurements. When mean percent accuracies were compared, there was no significant difference between tooth types for rotation, but there was for extrusion. A Bonferroni post-hoc test concluded that the mean accuracies for maxillary canine extrusion (41.7%) and mandibular canine extrusion (27.1%) were significantly lower than that of the maxillary central incisor (66.3%) at $P < 0.05$.

When comparing teeth that had spacing or IPR to those without, the mean accuracy for both conditions was 57%. An independent *t* test showed that for all teeth, IPR or spacing only slightly improved accuracy by 0.2% [standard deviation, 28.9; 95% CI, −7.7 to 8.2], and this did not reach statistical significance ($P > 0.05$).

Table I. Descriptive statistics for optimized rotation attachments

Tooth	*Movement*	*n*	*Mean*	*Standard deviation*
Maxillary canine	Predicted (°)	38	14.26	9.97
	Achieved (°)		9.71	7.37
	|Predicted − achieved| (°)		4.94	6.62
	Accuracy (%)		65.9	22.9
Maxillary premolar	Predicted (°)	36	12.65	12.73
	Achieved (°)		9.68	8.83
	|Predicted − achieved| (°)		3.54	5.86
	Accuracy (%)		72.8	23.6
Mandibular canine	Predicted (°)	35	15.49	11.04
	Achieved (°)		12.23	9.61
	|Predicted − achieved| (°)		3.89	4.60
	Accuracy (%)		68.0	25.9
Mandibular premolar	Predicted (°)	54	14.42	8.49
	Achieved (°)		9.62	7.95
	|Predicted − achieved| (°)		5.74	5.59
	Accuracy (%)		58.6	28.3

Table II. Descriptive statistics for conventional rotation attachments

Tooth	*Movement*	*n*	*Mean*	*Standard deviation*
Maxillary canine	Predicted (°)	17	11.18	7.29
	Achieved (°)		7.11	6.61
	|Predicted − achieved| (°)		4.45	4.59
	Accuracy (%)		57.9	29.8
Maxillary premolar	Predicted (°)	10	11.94	8.79
	Achieved (°)		5.08	2.83
	|Predicted − achieved| (°)		6.86	7.73
	Accuracy (%)		48.1	23.4
Mandibular canine	Predicted (°)	19	15.78	8.53
	Achieved (°)		9.50	7.71
	|Predicted − achieved| (°)		6.84	6.39
	Accuracy (%)		60.5	25.0
Mandibular premolar	Predicted (°)	26	14.41	8.93
	Achieved (°)		7.66	4.80
	|Predicted − achieved| (°)		6.84	8.23
	Accuracy (%)		58.6	28.3

DISCUSSION

The current study focused on intra-arch measurements of two tooth movements reported to be the least accurate with Invisalign—rotation of canines and premolars and extrusion of incisors and canines. These movements were also chosen because they have specifically optimized attachments available to compare to conventional ones. No published study to date has compared the efficacy of Invisalign's two attachment types for any tooth movement.

Table III. Descriptive statistics for optimized extrusion attachments

Tooth	*Movement*	*n*	*Mean*	*Standard deviation*
Maxillary central incisor	Predicted (mm)	11	1.45	0.77
	Achieved (mm)		1.36	1.25
	|Predicted − achieved| (mm)		0.52	0.37
	Accuracy (%)		58.7	24.6
Maxillary lateral incisor	Predicted (mm)	40	1.00	0.51
	Achieved (mm)		0.54	0.49
	|Predicted − achieved| (mm)		0.50	0.31
	Accuracy (%)		44.8	29.3
Maxillary canine	Predicted (mm)	19	1.01	0.85
	Achieved (mm)		0.52	0.48
	|Predicted − achieved| (mm)		0.50	0.53
	Accuracy (%)		46.6	35.7
Mandibular incisor	Predicted (mm)	9	1.10	0.87
	Achieved (mm)		0.72	0.54
	|Predicted − achieved| (mm)		0.38	0.42
	Accuracy (%)		64.8	24.3
Mandibular canine	Predicted (mm)	2	0.59	0.37
	Achieved (mm)		0.23	0.12
	|Predicted − achieved| (mm)		0.37	0.49
	Accuracy (%)		54.5	53.8

Because of the strict inclusion and exclusion criteria, the majority of the patients included in this study were Class I malocclusions, in which the clinicians had a preference of using optimized or conventional attachments to help resolve rotations or extrude teeth. Overall, the study sample was representative of the general, orthodontic population, as 99% of rotations and 95% of extrusion measured were considered to be mild (<45° and <2.5 mm, respectively), according to Align Technology's classifications.

A clinically discernible amount of malrotation was considered to be 15° on the basis of a previous study by Kravitz et al[2] that also assessed the accuracy of the Invisalign system. For extrusion, a 0.2 mm discrepancy was chosen to be clinically significant because that is the limit of resolution of the human eye,[15] and because

Table IV. Descriptive statistics for conventional extrusion attachments

Tooth	*Movement*	*n*	*Mean*	*Standard deviation*
Maxillary central incisor	Predicted (mm)	11	1.37	1.21
	Achieved (mm)		0.94	0.73
	|Predicted − achieved| (mm)		0.44	0.53
	Accuracy (%)		73.9	18.4
Maxillary lateral incisor	Predicted (mm)	30	1.03	0.58
	Achieved (mm)		0.51	0.37
	|Predicted − achieved| (mm)		0.52	0.37
	Accuracy (%)		48.3	23.7
Maxillary canine	Predicted (mm)	13	1.23	0.75
	Achieved (mm)		0.45	0.43
	|Predicted − achieved| (mm)		0.78	0.57
	Accuracy (%)		34.5	28.0
Mandibular incisor	Predicted (mm)	7	1.46	0.67
	Achieved (mm)		0.55	0.66
	|Predicted − achieved| (mm)		0.92	0.29
	Accuracy (%)		27.7	33.3
Mandibular canine	Predicted (mm)	5	1.00	0.47
	Achieved (mm)		0.22	0.28
	|Predicted − achieved| (mm)		0.77	0.30
	Accuracy (%)		16.1	18.8

Table V. Comparison of optimized and conventional attachments

Tooth movement	*n*	*Absolute mean difference (|Conventional − optimized|)*	*Standard deviation*	P *value*
Rotation	235	1.61°	6.11	0.0638
Extrusion	147	0.14 mm	0.42	0.0523

Tooth movement	*n*	*Mean accuracy difference (%) (Optimized − conventional)*	*Standard deviation*	P *value*
Rotation	235	7.3	26.4	0.0533
Extrusion	147	4.3	29.8	0.3819

Table VI. Comparison of mean predicted and achieved tooth movements

Attachment type	*n*	*Mean difference (Predicted − achieved)*	*Standard deviation*	P *value**
Optimized rotation (°)	163	4.01	6.22	<0.0001
Conventional rotation (°)	72	6.01	7.14	<0.0001
Optimized extrusion (mm)	81	0.40	0.47	<0.0001
Conventional extrusion (mm)	66	0.62	0.45	<0.0001

*Paired t test; statistical significance at $P < 0.05$.

Table VII. Mean accuracy of tooth movements

	Rotation			*Extrusion*		
Tooth	*n*	*Mean accuracy (%)*	*Standard deviation*	*n*	*Mean accuracy (%)*	*Standard deviation*
Maxillary central incisor				22	66.3	22.6
Maxillary lateral incisor				70	46.3	26.9
Maxillary canine	55	63.4	25.2	32	41.7	32.9
Maxillary premolar	46	67.4	25.5			
Mandibular incisor				16	48.5	33.5
Mandibular canine	54	65.4	25.6	7	27.1	32.7
Mandibular premolar	80	59.3	28.7			

orthodontists are trained to focus on anterior microesthetics during the finishing stages of treatment. When comparing optimized and conventional attachments, the mean difference for rotation was 1.61° or 7.3%. For extrusion, the mean difference was 0.14 mm or 4.3%. Though optimized attachments had a higher mean accuracy than conventional attachments for both movements, these differences were neither clinically nor statistically significant. This may be because most of the conventional rotation attachments used were rectangular and 3 mm long, which are typically larger than optimized attachments. A larger attachment provides a greater surface area for the aligner to push on, thus improving efficacy. In addition, many clinicians choose to bevel conventional horizontal attachments gingivally, resembling the design of optimized extrusion attachments. This configuration provides a surface perpendicular to the force vector needed for the extrusion of anterior teeth. Optimized extrusion attachments may still be more effective because of the intentional gap left between the attachment and aligner and between the tooth and aligner on the incisal surface. This space is meant to allow clearance for the tooth to extrude unimpeded.

In general, it was found that for all tooth movements, predicted values were higher than achieved values, and these results were statistically significant. For rotation, the mean difference between predicted and achieved values ranged from 4.01° to 6.01° for optimized and conventional attachments, respectively. Although these discrepancies were not clinically significant, practitioners may still elect to overcorrect canine and premolar rotations by 5 ± 1° on the basis of the findings of this study. For extrusion, the mean difference ranged from 0.40 mm to 0.62 mm for optimized and conventional attachments, respectively. Because these differences are to be considered clinically significant, clinicians should not only plan to overcorrect anterior extrusion, but they should also be mindful about how the prescribed tooth movement is staged. This is because it is likely that some extrusion or intrusion observed with clear aligners is "relative" and because of retroclination and proclination, respectively. In fact, anterior extrusion may be more predictable if the teeth are initially proclined labially and then retracted through space closure, rather than if overcorrected by 0.5 ± 0.1 mm (the discrepancy found in this study).

A study by Kravitz et al[2] found that the least accurate tooth movement with Invisalign was extrusion of incisors (29.6%) and that, for rotation, the least accurate tooth was the canine (35.8%). The same study also reported that for rotations greater than 15°, accuracy significantly fell by up to 52.5%. According to the literature, derotation of a cylindrical tooth is difficult because aligners tend to lose anchorage and slip off because of a lack of undercuts and the round tooth shape.[10] It would make sense that well-designed attachments would provide more retention and an active surface area for forces to be applied to, as long as the aligners fit well. Even though Kravitz et al[7] found that the presence of attachments did not significantly improve the accuracy of canine rotation, the most common attachment in that study was the vertical ellipsoid, which is rarely used today.

A systematic review reported 29.1%-49.7% accuracy for canine and premolar derotation.[11] The current study found a mean accuracy of 63.2% for these rotational movements and 47.6% for extrusion of anterior teeth. These findings are higher than previous studies show. Differences may be due to several factors, including the introduction of SmartTrack material in 2013, smaller sample sizes in previous studies, variable patient compliance, frequency of aligner switches, and the presence or absence of attachments. The overall mean accuracy of tooth movements in this study was found to be 57.2%, but it must be noted that only rotation and extrusion were analyzed in patients without any treatment adjuncts, such as interarch elastics. Therefore, these results should not be generalized for all patients treated with the Invisalign system. However, this study does provide useful information on the accuracy of these two difficult tooth movements and the efficacy of attachment types used over a series of aligners.

A recent study by Charalampakis et al[6] found that intrusion was the least accurate of all linear movements and that extrusion of incisors appeared to be accurate. This disagrees with previous findings and may be because of unplanned intrusion of posterior teeth superimposed on. The intrusion of posterior teeth between 0.25 mm to 0.5 mm is often observed with Invisalign because of plastic thickness.[1] Because each aligner is 0.75 mm thick occlusally,[16] the appliance has a posterior bite-block effect, which would cause the incisors to appear to extrude more than planned.[6] In addition, because only adult patients were used in the previous study, the eruption of posterior teeth was likely not encountered, so anterior intrusion would have appeared to be less accurate than extrusion. To overcome this limitation, control teeth were used in the current study to measure true achieved extrusion. These control teeth happened to extrude or intrude between 0 mm and 0.5 mm, likely because of second molar intrusion or eruption, respectively.

In this study, IPR and spacing were grouped because both conditions would, in theory, reduce friction and collisions between teeth during movement. Kravitz et al[7] reported that IPR improved the accuracy of canine rotations but that this was not statistically significant. The findings from the current study also found that there was no significant improvement in accuracy when IPR was used or when spacing was present, with both the presence and absence of these conditions reaching 57% accuracy. However, a small sample size of teeth had IPR or spacing (16%). In addition, IPR is most commonly performed on mandibular anterior teeth to help resolve crowding, and anterior rotations were not evaluated in this study.

The study sample included 37 patients that were aged <18 years. Of these, 16 patients were aged between 11 and 14 years who were growing and may have had second molars erupting. Although control teeth were used, both of these patient factors may have affected digital model superimposition on posterior teeth, as every case used for this study was superimposed on second molars, at a minimum. Although control teeth were thought to have moved in the vertical dimension because of posterior intrusion or eruption, they may also have moved if they had an attachment on them for planned movement in a different plane of space or simply for support of the aligner.

Other limitations of this retrospective study included the inability to account for certain variables, such as periodontal support, conventional attachment features, simultaneous tooth movements, and patient compliance. Though most of the patients used initial scans, this study also used refinement scans of some patients that already had prior tooth movement. Any existing mobility and altered periodontal support may have influenced results, along with general periodontal status and bone density ranging from patient to patient. Furthermore, the location, size, orientation, and beveling of conventional attachments were not considered. Although having an optimized rotation and extrusion attachment applied indicates that those were the primary movements for a specific tooth, it is possible that other minor simultaneous movements were occurring in different planes of space, compromising the predictability of the studied movements. As mentioned previously, some of the extrusion observed may have been due to retraction or retroclination rather than pure vertical movement. To overcome this, clinicians and researchers may consider planning more than one movement in separate stages for individual teeth. Pure movement may be possible with clear aligners because the plastic can act as a boundary for any other concurrent movements, unlike with fixed appliances. However, this is still difficult to achieve because most clear aligner systems, including Invisalign, do not require the use of radiographs, and thus, do not take into account a tooth's root length, angulation, and center of resistance when planning movements. Relying solely on the digital crowns of teeth can reduce the accuracy of tooth movement, leading to "non-tracking" and even unwanted movements.

Future studies evaluating tooth movement should be prospective and consider using 2-dimensional lateral cephalograms or 3D cone-beam computed tomography imaging to superimpose on stable landmarks rather than posterior teeth, which may inadvertently move during orthodontic treatment. They should only include patients that were evaluated from the start of treatment to the end to assess final results. In addition, other attachment variables previously mentioned should be considered, and additional types of tooth movement assessed to further compare the efficacy of conventional and optimized attachments.

CONCLUSIONS

1. Differences between mean accuracies of tooth movements using Invisalign's optimized vs conventional attachments were neither statistically nor clinically significant. This applies to the derotation of canines and premolars and extrusion of incisors and canines, specifically.
2. There was a statistically significant difference between the amount of tooth movement that was predicted and the amount that was achieved. For extrusion, this was also clinically significant (>0.2 mm), but for rotation, it was not (<15°).
3. Derotation of canines and premolars was accomplished with a 63.2% mean accuracy, and extrusion of incisors and canines was achieved with a mean accuracy of 47.6%. Overall, the mean accuracy of both these movements was 57.2%.
4. IPR or spacing did not significantly affect accuracy for rotations of canines and premolars and for extrusion of anterior teeth. A larger sample size of teeth with this treatment or condition is needed for more definitive conclusions.

With more companies offering clear aligners and with the emergence of in-house 3D printing, one can feel confident in knowing that conventional attachment types may be just as effective as Invisalign's proprietary optimized attachments for rotations of canines and premolars and for extrusion of incisors and canines. However, to improve the predictability of anterior extrusion, clinicians may aim to achieve this movement primarily through retraction and space closure with gingivally beveled attachments and should plan for overcorrection of up to 0.5 ± 0.1 mm. Clinicians may also consider overcorrecting rotations by 5 ± 1° to improve accuracy with the Invisalign system. Even with planned overcorrection, patients should always be aware of the possibility of needing refinement aligners to achieve clinically acceptable results.

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AUTHOR CREDIT STATEMENT

Theresa Karras contributed to conceptualization, data curation, investigation, methodology, original draft preparation, and draft review and editing; Maharaj

Singh contributed to formal analysis and resources; Emelia Karkazis contributed to data curation; Dawei Liu and Ghada Nimeri contributed to study validation; Bhoomika Ahuja contributed to the methodology, project administration, supervision, and draft review and editing.

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