How well does Invisalign work? A prospective clinical study evaluating the efficacy of tooth movement with Invisalign

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Introduction: The purpose of this prospective clinical study was to evaluate the efficacy of tooth movement with removable polyurethane aligners (Invisalign, Align Technology, Santa Clara, Calif). **Methods:** The study sample included 37 patients treated with Anterior Invisalign. Four hundred one anterior teeth (198 maxillary and 203 mandibular) were measured on the virtual Treat models. The virtual model of the predicted tooth position was superimposed over the virtual model of the achieved tooth position, created from the posttreatment impression, and the 2 models were superimposed over their stationary posterior teeth by using ToothMeasure, Invisalign's proprietary superimposition software. The amount of tooth movement predicted was compared with the amount achieved after treatment. The types of movements studied were expansion, constriction, intrusion, extrusion, mesiodistal tip, labiolingual tip, and rotation. **Results:** The mean accuracy of tooth movement with Invisalign was 41%. The most accurate movement was lingual constriction (47.1%), and the least accurate movement was extrusion (29.6%)— specifically, extrusion of the maxillary (18.3%) and mandibular (24.5%) central incisors, followed by mesiodistal tipping of the mandibular canines (26.9%). The accuracy of canine rotation was significantly lower than that of all other teeth, with the exception of the maxillary lateral incisors. At rotational movements greater than 15°, the accuracy of rotation for the maxillary canines fell significantly. Lingual crown tip was significantly more accurate than labial crown tip, particularly for the maxillary incisors. There was no statistical difference in accuracy between maxillary and mandibular teeth of the same tooth type for any movements studied. **Conclusions:** We still have much to learn regarding the biomechanics and efficacy of the Invisalign system. A better understanding of Invisalign's ability to move teeth might help the clinician select suitable patients for treatment, guide the proper sequencing of movement, and reduce the need for case refinement. (Am J Orthod Dentofacial Orthop 2009; 135:27-35)

In 1998, Align Technology (Santa Clara, Calif) introduced Invisalign, a series of removable polyurethane aligners, as an esthetic alternative to fixed labial braces. The Invisalign system uses CAD/CAM stereolithographic technology to forecast treatment and fabricate many custom-made aligners from a single impression.[1] Each aligner is programmed to move a tooth or a small group of teeth 0.25 to 0.33 mm every 14 days.[2] This unique method of tooth movement has involved more adults with orthodontic therapy. In the past decade, Invisalign has been used to treat over 300,000 people worldwide,[3,4] most of them above 19 years of age.[5]

As Invisalign continues to grow in consumer demand and professional use, questions regarding the efficacy of this system remain. How well do removable aligners move teeth? Align Technology reports that 20% to 30% of patients treated with Invisalign might require either midcourse correction or refinement impressions to help achieve the pretreatment goals.[2] However, many orthodontists report that 70% to 80% of their patients require midcourse correction, case refinement, or conversion to fixed appliances before the end of treatment.[6,7]

There are few substantive controlled clinical trials pertaining to Invisalign. Lagravère and Flores-Mir[8] conducted a systematic review of the literature about the Invisalign system and found that it did not offer scientific evidence regarding the indication, efficacy, limitations, or treatment effects of Invisalign. To date, published data have primarily included case reports, commentaries, material studies, surveys, descriptive

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technical articles, 1 abstract, 2 restrospective comparative cohort studies, and only 2 clinical trials.[3]

In the first cohort study, Djeu et al[9] retrospectively compared the treatment results of Invisalign patients to those with conventional fixed appliances, using the American Board of Orthodontics (ABO) objective grading system. The authors reported that the Invisalign group scored a mean 13 points higher and achieved a passing rate 27% lower than did the fixed appliance group. Invisalign scores were significantly lower for correcting posterior torque, occlusal contacts, anteroposterior occlusal relationships, and overjet.

In a follow-up study, Kuncio et al[4] compared the postretention dental changes of patients treated with Invisalign and conventional fixed appliances, using the ABO objective grading system. The Invisalign group consisted of patients treated in the 2005 treatment outcome study.[9] The authors reported that patients treated with Invisalign had more relapse than those treated with fixed appliances, particularly in the maxillary anterior teeth.

In the first clinical trial, Bollen et al[10] compared the effects of material stiffness and activation frequency on the ability to complete Invisalign treatment. The authors concluded that subjects with a 2-week activation frequency, no planned extractions, and low peer assessment rating score were more likely to complete their initial series of Invisalign aligners. The overall completion rate of initial aligners for patients who had 2 or more premolars extracted was only 29%. All subjects who completed their initial series of aligners required case refinement or conversion to fixed appliances.

In the second clinical trial, Clements et al[11] compared the effects of material stiffness and activation frequency on the quality of treatment measured by changes in peer assessment rating scores. The authors concluded that the aligners were most successful in improving anterior alignment, moderately successful at improving the midline and overjet, and least successful in improving buccal occlusion, transverse relationships, and overbite. Single mandibular incisor extraction sites reported significantly greater space closure than either maxillary or mandibular premolar extraction sites.

The landmark studies of Bollen et al[10] and Clements et al[11] marked the beginning of independent prospective clinical research regarding Invisalign. However, neither study used aligners that were identical to Invisalign's current aligner material or evaluated the efficacy of tooth movement with Invisalign. Further clinical trials are needed to assess the strengths and limitations of Invisalign treatment.

The purpose of this prospective clinical study was to evaluate the efficacy of tooth movement with Invisalign. The amount of tooth movement predicted by ClinCheck (Align Technology, Santa Clara, Calif) was compared with the amount achieved after Invisalign treatment. Tooth movement was evaluated on ToothMeasure, Invisalign's proprietary virtual model superimposition software. The types of tooth movement studied were expansion, constriction, intrusion, extrusion, mesiodistal tip, labiolingual tip, and rotation.

MATERIAL AND METHODS

The sample comprised 401 anterior teeth (198 maxillary, 203 mandibular) measured from the virtual models of 37 participants (14 men, 23 women). Each patient was treated with Anterior Invisalign in the Department of Orthodontics at the University of Illinois at Chicago. The participants included 23 whites, 9 Hispanics, 2 blacks, 2 East-Indians or Middle Easterns, and 1 Asian. Their mean age was 31 years. Sample Invisalign treatment included 30 dual arch, 3 maxillary arch only, and 4 mandibular arch only. The mean number of aligners per treatment was 10 maxillary and 12 mandibular. The mean amounts of anterior interproximal reduction (IPR) were 1.3 mm in the maxilla and 1.6 mm in the mandible. The frequency of anterior IPR was 180 of 401 teeth (45%). Tooth attachments varied in shape, size, and position according to the doctor's prescription. The frequency of anterior tooth attachments was 68 of 401 teeth (17%).

The patients were selected from the Department of Orthodontics at the University of Illinois at Chicago by 2 orthodontists: the faculty member supervising the treatment and the faculty member assigned to oversee all participants (B.K.). The one supervising the treatment first determined whether the malocclusion could be appropriately treated with anterior Invisalign. Patients deemed acceptable were then screened by the overseer. Only after approval from both faculty members was the patient selected for the study.

The inclusion criteria for patient selection were the following. (1) The patient qualified for anterior Invisalign with less than 5 mm of anterior crowding or spacing and adequate buccal interdigitation. Patients with posterior edentulous spaces were included if treatment did not entail space closure. Patients who would have mandibular incisor extractions were included in this study. Only 1 participant was treated with mandibular incisor extraction. (2) The patient was at least 18 years of age to allow for proper consent. (3) No special instructions could be requested on ClinCheck to alter the sequence or the speed of tooth movement. Clinicians were allowed to request or refuse IPR, proclination, attachments, and overcorrections on ClinCheck at their discretion. (4) No auxiliaries other than

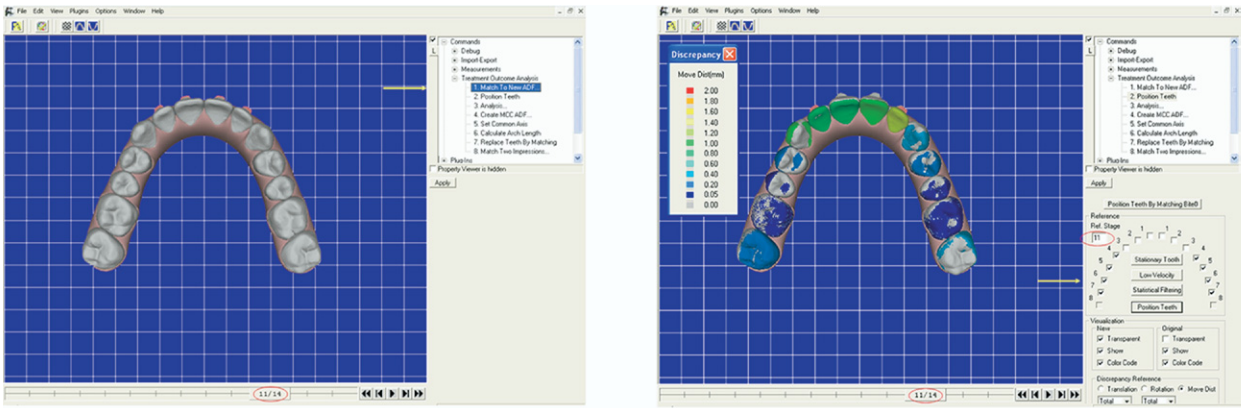

Fig 1. A, The final stage of tooth movement (*red oval*), corresponding to the predicted tooth position. The posttreatment Treat model was then selected from the data bank to be transferred into ToothMeasure (*yellow arrow*). **B,** Highly matched stationary posterior teeth were selected for superimposition by clicking on the appropriate boxes (*yellow arrow*). The accuracy of posterior superimposition and the efficacy of anterior tooth movement can be seen with the color-coded DI legend.

Invisalign attachments could be used during treatment, and the tray could not be altered with scissors or thermopliers.

These subjects were instructed to wear each aligner 22 hours a day, 7 days a week for 2 to 3 weeks. All patients were asked to complete a daily compliance log during treatment, recording the number of hours the aligners were worn each day.

After completing the initial series of aligners, posttreatment polyvinyl siloxane impressions were mailed to Align Technology. Two Align technicians assigned to our study e-mailed the pretreatment and posttreatment virtual Treat models back to our department, where they were deidentified and stored. Pretreatment digital models were transferred into ToothMeasure to score the discrepancy index (DI) by using a modified ABO objective grading system. Because treatment involved correction of the anterior teeth exclusively, the DI was scored only on overjet, overbite, anterior open bite, and crowding.

ToothMeasure is a software application developed by Align Technology used internally to provide measurements on scanned computer models. The software measures the shape of each tooth, intra-arch values (tip, torque [labiolingual tip], rotation, crowding, and alignment), and interarch values (overjet, overbite, occlusal contacts, occlusal relationship, and discrepancy). It enables 1 operator (N.D.K.) to reproducibly superimpose 2 digital models on user-selected reference points, such as untreated teeth, palatal rugae, and dental implants. Teeth can be superimposed within accuracies of 0.2 mm and 1.0°.[12,13]

The final stage of the pretreatment model was superimposed on the zero stage of the posttreatment model. The final stage of the pretreatment model corresponded to the predicted tooth position. The zero stage of the posttreatment model corresponded to the achieved tooth position. The 2 models were superimposed over their untreated stationary premolars and molars (Fig 1). ToothMeasure provided a matching results report on the accuracy of the pretreatment and posttreatment impressions. Posterior teeth that poorly matched between the 2 impressions were not selected for superimposition (Fig 2). For patients with missing posterior teeth, the remaining teeth were used for superimposition.

Once the 2 models were superimposed, ToothMeasure performed an efficacy analysis report, which showed quantitative measurements for the predicted and achieved movements. The percentage of accurate tooth movement was determined by the following equation: percentage of accuracy = 100% − [(|predicted-achieved|/|predicted|) × 100%]. The equation accounted for directionality and ensured that the percentage of accuracy never exceeded 100% for teeth that achieved movements beyond their predicted value. The tooth movements evaluated were labial expansion, lingual constriction, intrusion, extrusion, mesiodistal tip, labiolingual tip, and rotation. Translational tooth movements (expansion, constriction, intrusion, extrusion, and mesiodistal tip) were measured in millimeters. Rotational tooth movements (labiolingual tip and rotation) were measured in degrees.

All statistical analyses were performed with SPSS software (SPSS, Chicago, Ill). Accuracy was deter-

Fig 2. A, Poorly matched right and left second molars indicated by the matching report. **B,** The second molars were deselected for superimposition (*black arrows*). Note the improvement in superimposition of the remaining 6 posterior teeth and the greater deviation in the position of the anterior teeth.

mined by the amount of tooth movement achieved divided by the amount attempted. A 1-way analysis of variance (ANOVA) test ($P < 0.05$) compared the mean percentage of accuracy for each type of movement. The Scheffé test ($P < 0.05$) ascertained which teeth, within that movement, had a significant difference in accuracy. Paired *t* tests ($P < 0.05$) compared the accuracy of canine rotations greater than 15° and less than 15°. Paired *t* tests ($P < 0.05$) also compared the accuracy of labial crown tip vs lingual crown tip for each anterior tooth. An ANOVA test determined the significance of the modified DI on the accuracy of each type of movement.

RESULTS

Thirty-eight consecutively treated patients were enrolled in the clinical study. Of them, 37 completed anterior Invisalign treatment according to the research protocol. One patient could not complete his treatment in time for data collection. One clinician deviated from the protocol by using elastics to extrude a maxillary incisor. For this patient, only the mandibular arch was evaluated.

Patient compliance forms were collected at the end of treatment; all patients reported wearing their aligners for 21 to 23 hours per day. The last data collection was in December 2006. All predicted translational movements less than 0.2 mm and rotational movements less than 1.0° were eliminated from the analysis to account for the error in model superimposition.

The mean accuracy of Invisalign for all tooth movements was 41% (Table I). The highest accuracy was achieved during lingual constriction (47.1%), and the lowest accuracy was during extrusion (29.6%). More specifically, the most accurate tooth movements were lingual constriction of the mandibular canines (59.3%) and lateral incisors (54.8%), followed by rotation of the maxillary central incisors (54.2%). The least accurate tooth movements were extrusion of the maxillary (18.3%) and mandibular (24.5%) central incisors, followed by mesiodistal tip of the mandibular canines (26.9%) (Fig 3). An acceptable sample size was attained for all tooth movements, with the exception of extrusion of the mandibular lateral incisors (n = 4) and canines (n = 3). All movements had large standard deviations (mean SD = 32.9).

When analyzing the accuracies of each movement, only rotation ($P = 0.001$) had a significant difference in accuracy between teeth (Table II). The accuracy of rotation for the maxillary canines (32.2%) was significantly lower than that of the maxillary central incisors (54.2%) and mandibular lateral incisors (51.6%). The accuracy of rotation for the mandibular canines (29.1%) was significantly lower than that of the maxillary central, mandibular central (48.8%), and mandibular lateral (51.6%) incisors (Fig 4 and Table III).

The accuracy of rotation for the maxillary and mandibular canines was further evaluated after separating the sample into 2 groups: predicted rotations less than 15° and predicted rotations greater than 15° (Table IV). Fifteen degrees was chosen as a clinically discernable amount of malrotation. For rotations greater than

Table I. Accuracy of tooth movements

	Labial expansion			Lingual constriction			Intrusion			Extrusion		
Tooth	*Mean (%)*	*n*	*SD*	*Mean (%)*	*n*	*SD*	*Mean (%)*	*n*	*SD*	*Mean (%)*	*n*	*SD*
Max central	48.5	13	37.9	51.8	32	34.0	44.7	39	30.0	18.3	12	24.8
Max lateral	49.0	14	37.3	40.4	30	34.4	32.5	22	22.1	28.4	23	33.2
Max canine	36.0	13	38.0	34.7	17	33.5	40.0	17	34.0	49.9	11	30.5
Mand central	27.4	24	31.9	46.7	14	41.5	46.6	37	29.6	24.5	11	37.0
Mand lateral	50.8	30	34.5	54.8	14	38.0	40.0	42	30.4	28.4	4	35.1
Mand canine	29.9	15	33.0	59.3	13	37.4	39.5	32	30.2	30.4	3	36.2
Total	40.5	109	35.6	47.1	120	35.9	41.3	189	29.5	29.6	64	32.5

	Tip (MD)			Tip (LL)			Rotation		
Tooth	*Mean (%)*	*n*	*SD*	*Mean (%)*	*n*	*SD*	*Mean (%)*	*n*	*SD*
Max central	38.6	26	36.1	40.3	51	33.0	54.2	52	26.6
Max lateral	43.1	39	37.3	47.6	53	36.0	43.4	59	28.8
Max canine	35.5	17	34.3	44.6	31	33.0	32.2*	57	28.6
Mand central	39.6	37	34.2	44.2	39	35.8	48.8	64	27.5
Mand lateral	48.6	41	35.1	47.4	49	34.2	51.6	57	29.8
Mand canine	26.9	20	33.8	43.7	34	33.9	29.1*	55	26.3
Total	40.5	180	35.4	44.7	257	34.2	43.2	344	29.3

Max central, Maxillary central incisor; *Max lateral,* maxillary lateral incisor; *Max,* maxillary; *Mand central,* mandibular central incisor; *Mand lateral,* mandibular lateral incisor; *Mand,* mandibular; *MD,* mesiodistal; *LL,* labiolingual.
**P* <0.05.

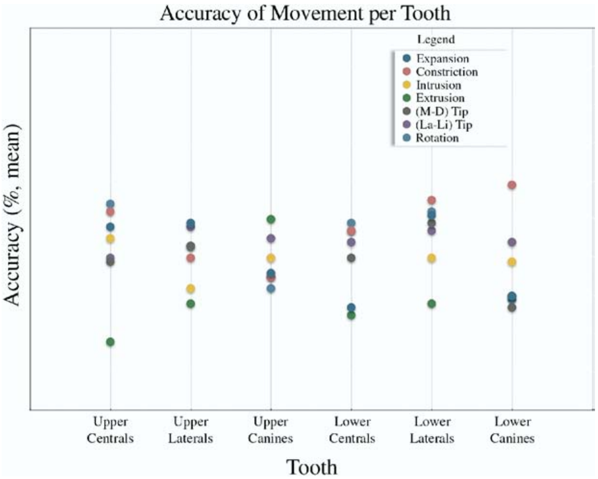

Fig 3. Scattergram.

15°, the accuracy of maxillary canine movement was significantly reduced.

The accuracy of labiolingual crown tip was further evaluated after separating the sample into 2 groups: labial crown tip and lingual crown tip (Table V). Lingual crown tip (53.1%) was significantly more accurate than labial crown tip (37.6%), particularly for the maxillary incisors.

The accuracy of labiolingual tip was significantly influenced ($P = 0.022$) by the difficulty of the pretreatment malocclusion (modified DI score) (Table VI). No other movements were significantly influenced by the patient's modified DI score.

Table II. Accuracy of tooth movements

Accuracy	*df*	*Mean square*	*F*	*Significance*
Expansion	5	2,221.279	1.818	0.116
Constriction		1,483.111	1.157	0.335
Intrusion		677.619	0.771	0.572
Extrusion		1,282.138	1.233	0.306
Tip (MD)		1,442.048	1.154	0.334
Tip (LL)		361.795	0.305	0.910
Rotation*		6,036.802	7.705	0.001

MD, Mesiodistal; *LL,* labiolingual.
**P* <0.05.

To account for the accurate movements hidden in the large standard deviation, the entire sample was evaluated for movements with greater than 70% accuracy. In spite of the relatively low mean accuracy for each movement, over a quarter of all tooth movements in the study were over 70% accurate.

DISCUSSION

Designing a study that appropriately tested the efficacy of Invisalign was particularly challenging. A retrospective study can fail to control for patient compliance or modifications in treatment, whereas a controlled, prospective study might not use a clinical

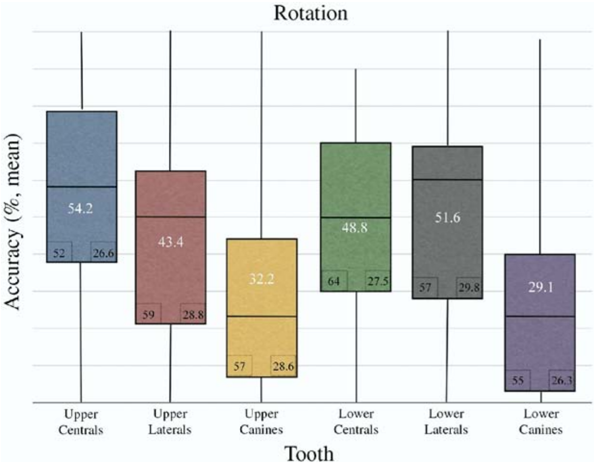

Fig 4. Box plots providing information about sample distribution, skew, and range of data. The upper and lower boundaries of the rectangle indicate the upper and lower quartiles, respectively. The *black line* inside the rectangle indicates the median. The distance between the median and the quartile indicates the skew of the data. The 2 lines (*whiskers*) extending from the box indicate the extreme values. The mean percentage accuracy, sample number (*n*), and standard deviation (*SD*) are shown in the box. Maxillary and mandibular canine rotations were significantly less accurate than any other teeth, with the exception of the maxillary lateral incisor. There was no statistical difference in accuracy between maxillary and mandibular teeth of the same tooth type.

protocol that maximizes use of the appliance. Also, each clinician has his or her own theories of the best methods for moving teeth with Invisalign. Therefore, our results are best interpreted with the perspective that we have simply taken the first step in a long journey of better understanding the Invisalign system and quantifying empirical knowledge.

Our most evident finding was that great variation exists in regards to treatment efficacy with Invisalign. The mean accuracy of tooth movement was 41%. These results are slightly lower than the internal findings of Nguyen and Cheng,[13] who reported a mean accuracy of anterior tooth movement of 56%. In spite of the relatively low mean accuracy, all tooth movements had large standard deviations (mean SD, 32.9), and a quarter of all tooth movements were over 70% accurate.

The most accurate tooth movement was lingual constriction (47.1%). Compared with labial expansion (40.5%), the accuracy of constriction was nearly identical for every tooth, with the exception of the mandibular central incisors and canines. It was nearly twice as accurate to retract these teeth than to expand them labially. These data suggest that Invisalign can achieve greater accuracy in closing mandibular anterior spaces than alleviating mandibular anterior crowding with labial expansion alone. The clinician might consider aligning blocked-out mandibular canines primarily with IPR, rather than by expansion and proclination.

The least accurate tooth movement was extrusion (29.6%). The maxillary (18.3%) and mandibular (24.5%) central incisors had the lowest accuracy for extrusion. The maxillary lateral incisors were by far the most commonly extruded teeth (n = 23). Only 13 of the 64 teeth had attempted extrusions greater than 1.0 mm (range, 1.0-1.8 mm), and no tooth had an attempted extrusion greater than 2 mm. The average amount of extrusion attempted was 0.56 mm. The difficulty in extrusive movement was most likely because the aligner poorly grasped the tooth during vertical pull. Therefore, prescribing even minor extrusive movements might justify overcorrection, attachments, and auxiliaries. Boyd[6] reported that absolute extrusion is still challenging even with attachments and advocated extruding teeth with an elastic from a button on the tooth's facial aspect. Alternatively, the clinician could consider combining extrusion with more accurate movements such as retraction (lingual constriction) or retroclination to improve the predictability of tooth movement (Fig 5).

Boyd and Vlaskalic[14] reported that correction of a deep overbite is highly predictable with Invisalign. Likewise, Nguyen and Cheng[13] reported that the mean accuracy of anterior intrusion was 79%. In our study, the mean accuracy of anterior tooth intrusion was only 41.3%. The highest accuracy of intrusion was achieved by the maxillary (44.7%) and mandibular (46.6%) central incisors. The maxillary lateral incisors had the lowest accuracy of intrusion, this probably resulted from poor tracking of the adjacent canine. Only 41 of the total 189 teeth had attempted intrusions greater than 1.0 mm (range, 1.0-2.1 mm), and only 2 teeth had attempted intrusions greater than 2 mm. The average amount of intrusion attempted was 0.72 mm. Although improvement of anterior overbite has been reported, significant correction of a deep overbite with Invisalign appears unlikely.[11]

The extent of mesiodistal movement with Invisalign has drawn great interest among clinicians, particularly as more practitioners attempt correction of anteroposterior malocclusions. Boyd and Vlaskalic[14] reported greater than 3 mm of maxillary molar distalization in a patient with a Class II Division 2 malocclusion. In contrast, Djeu et al[9] and Clements et al[11] reported difficulty with large anteroposterior movements using Invisalign. In our study, the mean accuracy

Table III. Post-hoc Scheffé test: rotation

Tooth (I)	*Tooth (II)*	*Mean difference (I-II)*	*Significnce*	*95% CI*	
				Lower	*Upper*
Max central	Max lateral	10.823	5.310	−6.997	28.643
	Max canine*	21.974	0.006	4.008	39.940
	Mand central	5.342	0.959	−12.148	22.833
	Mand lateral	2.588	0.999	−15.377	20.554
	Mand canine*	25.106	0.001	6.985	43.228
Max lateral	Max canine	11.151	0.468	−6.248	28.551
	Mand central	−5.480	0.947	−22.389	11.428
	Mand lateral	−8.234	0.775	−25.634	9.165
	Mand canine	14.283	0.195	−3.276	31.844
Max canine	Mand central	−16.631	0.062	−33.694	0.430
	Mand lateral*	−19.285	0.019	−36.935	−1.836
	Mand canine	3.132	0.997	−14.575	20.840
Mand central	Mand lateral	−2.753	0.998	−19.816	14.308
	Mand canine*	19.764	0.013	2.538	36.990
Mand lateral	Mand canine*	22.518	0.003	4.810	40.226

Max central, Maxillary central incisor; *Max lateral,* maxillary lateral incisor; *Max,* maxillary; *Mand central,* mandibular central incisor; *Mand lateral,* mandibular lateral incisor; *Mand,* mandibular.
$^*P < 0.05$.

Table IV. Accuracy of canine rotation: <15° vs >15°

Tooth	*Predicted <15°*			*Predicted >15°*			*df*	*t*	*Significance*
	Mean (%)	*n*	*SD*	*Mean (%)*	*n*	*SD*			
Max canine*	35.8	45	29.4	18.8	12	14.1	33.0	2.759	0.009
Mand canine	27.9	43	28.6	33.2	12	15.9	32.6	−0.830	0.413

Max, Maxillary; *Mand,* mandibular.
$^*P < 0.05$.

Table V. Labial crown tip vs lingual crown tip

Tooth	*Labial crown tip*			*Lingual crown tip*			*df*	*t*	*Significance*
	Mean (%)	*n*	*SD*	*Mean (%)*	*n*	*SD*			
Max central*	26.9	22	25.6	50.5	29	34.8	49	−2.780	0.008
Max lateral*	35.4	24	37.4	57.6	29	32.1	46	−2.290	0.027
Max canine	38.3	17	31.2	52.3	13	36.0	24	−1.120	0.274
Mand central	39.2	28	35.4	56.8	11	35.4	18	−1.399	0.178
Mand lateral	40.7	29	34.8	57.0	20	31.7	43	−1.690	0.097
Mand canine	44.8	19	37.7	42.5	15	29.8	32	0.198	0.845
Total*	37.6	139	33.9	53.1	117	32.9	249	−3.720	0.000

Max central, Maxillary central incisor; *Max lateral,* maxillary lateral incisor; *Max,* maxillary; *Mand central,* mandibular central incisor; *Mand lateral,* mandibular lateral incisor; *Mand,* mandibular.
$^*P < 0.05$.

of mesiodistal tip was 40.5%. Only 21 of 180 teeth had attempted mesiodistal movement greater than 1.0 mm (range, 1.0-3.8 mm), and only 8 teeth had attempted movement greater than 2 mm. The highest accuracy was achieved by the maxillary (43.1%) and mandibular (48.6%) lateral incisors. The maxillary (35.5%) and mandibular (26.9%) canines and the maxillary central incisors (38.6%) had the lowest accuracy. These data suggest that teeth with larger roots might have greater difficulty achieving mesiodistal movement.

Lingual crown tip (53.1%) was significantly more accurate than labial crown tip (37.6%), particularly for the maxillary incisors. It was nearly twice as accurate to retrocline the maxillary central incisors as to procline

Table VI. Influence of modified DI score on accuracy

DI	*df*	*Mean square*	*F*	*Significance*
Expansion	1	0.376	3.027	0.085
Constriction		0.292	2.281	0.134
Intrusion		0.007	0.086	0.770
Extrusion		0.068	0.650	0.424
MD tip		0.222	1.808	0.181
LL tip*		0.616	5.289	0.022
Rotation		0.185	2.180	0.141

MD, Mesiodistal; *LL,* labiolingual.
*$P < 0.05$.

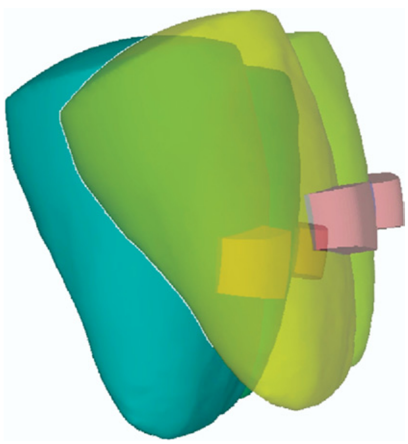

Fig 5. Relative extrusion. The clinician might consider combining extrusion with more predictable movements such as retraction (constriction) and retroclination.

them. Only 39 of 139 teeth had attempted labial tip greater than 5° (range, 5.0°-14.7°). Only 28 of the 117 teeth had attempted lingual tip greater than 5° (range, −5.0° to −10.0°). This information might be particularly useful for treatment of patients with Class II Division 2 malocclusion; overcorrection can be prescribed to procline maxillary central incisors but might not be needed to retrocline flared lateral incisors.

Rotation of the maxillary (32.2%) and mandibular (29.1%) canines was significantly less accurate than all other teeth, with the exception of the maxillary lateral incisors. Poor tracking of the maxillary canine might have influenced the movement of the adjacent lateral incisor. The highest accuracy of rotation was achieved by the maxillary central incisors (54.2%). These results are similar to findings of Nguyen and Cheng,[13] who reported that incisors achieved the highest accuracy of rotation (60%), and canines and premolars had the lowest accuracy of rotation (39%). In our study, 231 of the 344 teeth had attempted rotations greater than 5° (range, 5.0°-48°), and only 70 teeth had attempted

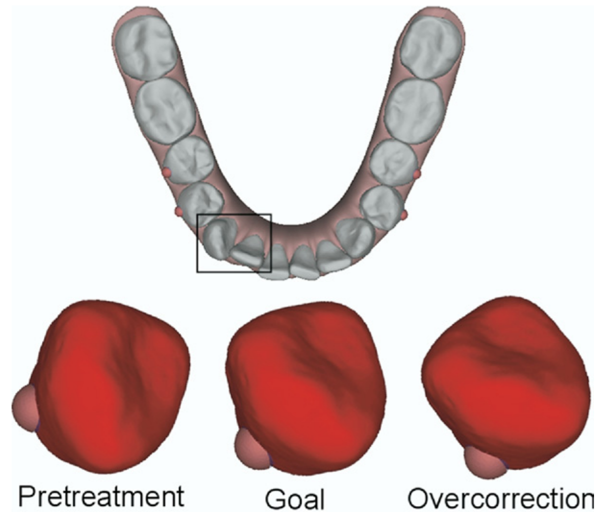

Fig 6. Significant overcorrection of rounded teeth might be necessary, in addition to facial and labial attachments or auxiliaries.

rotations greater than 15°. When rotations greater than 15° were attempted, the accuracy of the maxillary canine was significantly reduced. These data suggest that teeth with rounded crowns such as canines and premolars experience greater difficulty in correcting rotations. Boyd[6] recommended 10% overcorrection for canine and premolar rotations, but our results suggest that greater overcorrection might be indicated (Fig 6).

With the exception of canine rotation, no other tooth was significantly less accurate in its respective movement. Interestingly, there was no statistical difference in accuracy between maxillary and mandibular teeth of the same type for any movement studied. Therefore, crown shape might have a greater influence than crown size regarding the accuracy of tooth movement with Invisalign.

Case complexity had little influence on the accuracy of tooth movement. Only labiolingual tip had a significant relationship to the predictability of tooth movement. Therefore, the severity of pretreatment overjet might influence the accuracy of Invisalign. These results are similar to the findings of Djeu et al,[9] who reported that pretreatment overjet and anteroposterior occlusion significantly influenced the quality of Invisalign treatment. In this study, no attempt was made to correct the posterior occlusal relationship. Further research is needed assess the influence of case complexity, particularly the anteroposterior relationship, on the efficacy of Invisalign.

There were 5 significant limitations to this study. (1) Posterior tooth movement was not evaluated because of the need to superimpose on stationary teeth. Thus, the patients were of mild difficulty, and few translational movements exceeded 2 mm. (2) Clinicians were instructed not to use auxiliaries. Clearly, successful Invisalign treatment is not limited to aligners alone. Although this research protocol might have handicapped the treatment, it provides a baseline value to what can be achieved with aligners alone. (3) Overcorrections were not accounted for. Many clinicians in the study requested overcorrection, but the final predicted tooth position was the measurement used. Therefore, even movements with low accuracy might have achieved their desired tooth position. (4) Tooth movement could have been influenced by the patient's age, periodontal support, root length, and bone density. Because of limitations in the university's institutional review board approval, periapical radiographs were not permitted. (5) Patient satisfaction was not measured. The results might have had little clinical significance if the patients were satisfied with their posttreatment smile.

Future studies should incorporate lateral cephalometric or volumetric 3-dimensional cone-beam imaging to assess tooth movement with Invisalign, as an alternative to superimposing on stationary posterior teeth. Such studies will allow for the evaluation of posterior tooth movement and address questions regarding root movement with Invisalign.

CONCLUSIONS

In this prospective clinical study evaluating the efficacy of tooth movement with Invisalign, the following conclusions were made.

1. The mean accuracy of tooth movement with Invisalign was 41%. The most accurate tooth movement was lingual constriction (47.1%). The least accurate tooth movement was extrusion (29.6%). The mandibular canine was the most difficult tooth to control.
2. Maxillary and mandibular canines achieved approximately one third of the predicted rotation. The accuracy of canine rotation was significantly lower than the rotation of all other teeth, with the exception of the maxillary lateral incisors. At rotational movements greater than 15°, the accuracy for the maxillary canines was significantly reduced.
3. With the exception of canine rotation, no tooth was significantly less accurate in movement.
4. Lingual crown tip was significantly more accurate than labial crown tip, particularly for the maxilary incisors.
5. The severity of pretreatment overjet might influence the accuracy of anterior tooth movement with Invisalign.
6. There was no statistical difference in accuracy between maxillary and mandibular teeth of the same type for any tooth movement studied.

These results indicate that we still have much to learn regarding the biomechanics and efficacy of the Invisalign system. Clinicians who prescribe Invisalign treatment should fully recognize its limitations and commit themselves to providing the gold standard of care for their patients. Providing quality care, regardless of the treatment modality, is only way to truly be a premiere provider.

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