Comparative Analysis of Two Clear Aligner Systems for Orthodontic Refinement

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Submitted to the Graduate Faculty of the

School of Dental Medicine in partial fulfillment

of the requirements for the degree of

Master of Dental Science

University of Pittsburgh

2023

UNIVERSITY OF PITTSBURGH

SCHOOL OF DENTAL MEDICINE

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Comparison of Invisalign and 3M Clarity Clear Aligner Cases and the Most Common Movements Requiring Refinement

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Introduction:

The 3M Clarity™ Clear Aligner System differs from Invisalign in a variety of ways, such as algorithm, precision attachments, precision cuts, and appliance design. The main objective of this study is to answer the question if there is a difference in the most inaccurate tooth movements between two clear aligner systems. This study will provide a side-by-side comparison of cases with similar malocclusions treated with either Invisalign and 3M Clarity™ Clear Aligner System before starting their respective refinement stage.

Results:

Mandibular intercanine width expansion was the most inaccurate in the horizontal for Invisalign. Mandibular interpremolar width expansion was the most inaccurate in the horizontal for 3M Clarity Aligners. Mandibular incisor intrusion was the most inaccurate movement in the vertical for both Invisalign and 3M Clarity Aligners. Regarding rotations, the most inaccurate teeth for Invisalign were the mandibular canines and the most inaccurate teeth for 3M Clarity Aligners were the maxillary incisors.

Conclusions:

There were no statistically significant differences found between any of the tooth movements when comparing Invisalign with 3M Clarity Aligners. Even though there weren't any

statistical significances comparing the two aligner systems, Invisalign was more accurate in achieving maxillary lateral extrusion and 3M Clarity Aligners was more accurate in achieving maxillary central incisor rotation and mandibular intercanine width change.

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Introduction and Statement of the Problem

Clear aligner therapy to treat adult patients as an alternative to conventional braces is now routinely used worldwide as an acceptable treatment modality. Invisalign clear aligners were introduced in the late 1990s by Align Technology (Santa Clara, Calif) as a different approach to straighten teeth without the use of braces (Charalampakis et al., 2018). It was a novel system used to initially treat mild malocclusions, such as space closure and mild crowding. It has since progressed in its treatment planning skills, manufacturing of its materials, and attachment placements. Its powerful marketing campaign has helped increase the public demand for this company to help correct not only mild cases, but a variety of difficult malocclusions, and has integrated itself into orthodontic practices today (Simon et al., 2014).

Invisalign has since opened the door for other companies to develop their own clear aligner system that has since developed their own unique method for straightening teeth more efficiently. The 3M Clarity™ Clear Aligner System is unique among other clear aligner companies because it employs an exclusive, advanced algorithm to mimic specific orthodontic movements. Its core is artificial intelligence, meaning that a prospective analysis of preliminary data is essential for the algorithm to develop and improve its accuracy over time (Warshawsky 2019). The 3M Clarity™ Clear Aligner System differs from Align Technology in a variety of ways, such as algorithm, precision attachments, precision cuts, and appliance design. This proposes the question whether there would be a difference posttreatment between the two aligner systems. However, this question has not been answered in previous studies and there have been no studies found that scientifically compare Align Technology with the 3M Clarity™ Clear Aligner System.

Although clear aligner therapy in general has become higher in demand in patient care, there is no strong evidence evaluating the capabilities and limitations of clear aligners (Charalampakis et al., 2018). There are various limitations to using clear aligners with the main limitation being the lack of efficiency when treating certain tooth movements. The tooth movements found to be the most difficult to achieve include buccolingual inclination (torque), overjet, extraction space closure, interocclusal sagittal changes, occlusal contacts, and expansion (Robertson et al., 2019). Align Technology reports that 20% to 30% of patients treated with Invisalign might require refinement or midcourse correction to help achieve the pretreatment goals. However, many orthodontists report that 70% to 80% of their patients require refinement, midcourse correction, or transition to fixed appliances before the end of treatment (Kravitz et al., 2009). No previous studies have been found evaluating the percentage of patients requiring refinement by the 3M Clarity™ Clear Aligner System or by orthodontists using the system.

The main objective of this study is to answer the question if there is a difference in the most inaccurate tooth movements between two clear aligner systems. This study will provide a side-by-side comparison of cases with similar malocclusions treated with either Invisalign and 3M Clarity™ Clear Aligner System before starting their respective refinement stage. The evaluation will compare whether the most common movements required in each refinement is the same or different when evaluating Invisalign versus 3M Clarity™ Clear Aligners. The accuracy of the aligners will be evaluated by 3-dimensional superimposition of predicted and achieved models. Some of the clinical implications of performing this study include selecting a clear aligner system for your practice that is universal in treating the patient population in your area, selecting a specific clear aligner system for more difficult cases that require more difficult tooth movements, knowing when and how much to overcorrect certain tooth movements in the online prescription, and taking

the time to prepare the online prescription so that patient's malocclusion is corrected the most efficiently.

2.0 Specific Aims

Aim 1. Perform superimpositions of initial scans with predicted and achieved scans of patients treated with both the Invisalign and 3M Clarity™ Clear Aligner Systems prior to starting their respective refinement stages.

Aim 2. For every subject, perform 112 measurements (56 predicted and 56 achieved movements), which include horizontal movements, vertical movements, rotations, and transverse changes.

Aim 3. Perform descriptive statistical analysis for each movement and interpret the results to delineate any sbetween Invisalign and 3M Clarity™ Clear Aligners.

Aim 3. Identify which of the measurements had the largest discrepancy for Invisalign and 3M and compare if they shared a similar discrepancy or had differences.

3.0 Background and Literature Review

3.1 Efficacy of Tooth Movement

Although the research is limited, there are some clinical studies that have been performed evaluating the efficacy of tooth movement with Invisalign. A study done by Kravitz et al. in 2009 evaluated the efficacy of tooth movement with Invisalign by superimposing the virtual model of the predicted tooth position over the virtual model of the achieved tooth position. Their project reflected a study of a variety of types of movement, including intrusion, extrusion, expansion, constriction, rotation mesiodistal tip, and labiolingual tip. Their results showed the mean accuracy of tooth movement with Invisalign was 41%. Their data most relevant to this future study includes their most accurate movement being lingual constriction (47.1%), and the least accurate movement being extrusion (29.6%). To be more specific, extrusion of the maxillary (18.3%) and mandibular (24.5%) central incisors were the least accurate movements. They also found that there was no statistical difference in accuracy between maxillary and mandibular teeth of the same tooth type for any movements studied (Kravitz et al., 2009). Some limitations to this study include exclusion of posterior teeth and no classification of patients based on their pretreatment Angle classification.

A study performed by Simon et al. aimed to evaluate the efficacy of tooth movement with Invisalign but of specific tooth movements: incisor torque >10°, premolar derotation >10°, and molar distalization >1.5 mm. They sought to see if Invisalign auxiliary attachments and the staging of movements with each tray has any influence on the efficacy of treatment. Their results showed that the overall mean efficacy of Invisalign was 59%. The mean accuracy for upper incisor torque was determined to be 42%. The most effective movement was

determined to be distalization of an upper molar, with efficacy of 87%. The lowest accuracy was seen with premolar derotation at 40%. Their study did not evaluate refinements specifically but mentioned that practicing orthodontists should consider that overcorrections or case refinements may be needed, since in these cases the ClinCheck® simulation could predict more movement than what may result clinically (Simon et al., 2014).

Charalampakis et al. performed a retrospective study to determine how accurate Invisalign is at performing specific tooth movements. They evaluated specifically Class I adult patients who needed a refinement series of aligners after completing their first series. Predicted and achieved tooth movements were obtained after analyzing the participants' initial and predicted models from their respective ClinChecks. Their results showed that the most accurate movement achieved was horizontal movements of all incisors. The most inaccurate movements were found to be vertical movements (particularly intrusions of maxillary central incisors) and canine rotation (Charalampakis et al., 2018). They state in their study that they aimed to focus on the size of the difference between the predicted and achieved movements. Most previous studies discussed Invisalign's accuracy through percentages.

3.2 Clear aligner refinements

A question rises whether cases need to go into refinement or not. A study performed by Graf et al. measured the treatment effects of aligner treatments in adult patients directly after treatment and the stability of these effects after a short-term retention period. The malocclusion severity was rated differently than previous studies by using the PAR Index measured pretreatment, posttreatment, and after a mean retention period of 10 months. The results showed

that the cases were either classified as ‘improved’ or ‘greatly improved.’ Out of 33 patients used, only 6 patients needed a case refinement with a mean of 23 further aligners. The reason for this is that they found that more severe cases were not destined to need a case refinement compared to mild cases with a lower initial PAR score. Thus, they suggested that whether initial digital treatment planning will lead to predictable and realistic tooth movements does not necessarily and solely depend on the individual malocclusion but also on other factors. Some factors could include patients’ adherence to specific recommendations, such as how much they wore the aligners (Graf et al., 2021).

3.3 Clear aligners and Dental Monitoring

A study performed by Hansa et al. sought to compare the effects of Invisalign clear aligner treatment with and without Dental Monitoring (DM). They evaluated participants for their treatment duration, number of appointments, refinements needed and total refinement aligners, and accuracy to achieve predicted tooth movements. Their results found that the actual tooth positions were statistically more accurate for the DM group, specifically for rotational movement of the maxillary anterior teeth, and buccal-lingual linear movement of the mandibular anterior teeth. They did not specify the least accurate movement for either the DM or control group. They also found that there were nonstatistically significant differences in favor of the DM group in the number of refinements and in favor of the control group for the number of refinement aligners. No indications were given to the precise movements that needed to be corrected in the refinement stages. These results suggest that DM did not seem to affect aligner

treatment with regard to overall (Hansa et al., 2021). There's potential for the aligner outcomes to have occurred due to other unknown factors.

3.4 Efficacy in Treating Overbite

A study by Khosravi et al. aimed to investigate the vertical dimension changes in patients with various pretreatment overbite relationships treated only with Invisalign. They aimed to evaluate any dental or skeletal changes with the bite opening or closing. Their results showed that deep bite and open bite patients had a median opening or deepening of 1.5 mm. The median change for the normal overbite patients was 0.3 mm. Most of the improvements in the two groups was due to the changes in the incisor position. They also noted minimal changes in the molar vertical position and mandibular plane angle.

A retrospective study conducted by Blundell et al. aimed to investigate and determine the accuracy of Invisalign in correcting a deep overbite by comparing the outcomes predicted by the ClinCheck with the achieved posttreatment outcomes. Their results showed that the deeper the patient's initial overbite, the greater the discrepancy in overbite expression posttreatment. Also, the greater the amount of programmed reduction in overbite according to the ClinCheck, the larger the discrepancy in overbite expression posttreatment. Overall, only 39.2% of the prescribed overbite reduction was expressed when the ClinCheck over-predicted overbite reduction in 95.3% of all the patients.

3.5 Efficacy of Attachments

A retrospective study by Karras et al. aimed to compare the efficacy of optimized and conventional attachment types specifically on the extrusion of the anterior teeth and rotations of canines and premolars. Their reasoning for evaluating these two specific movements was because they are two of the most difficult movements to be achieved predictably with Invisalign. The goal of this study was to also help guide dentists in choosing more efficient attachment designs and considering overcorrection of movements where needed in the treatment plan in the clear aligner software. Their results showed that there were no statistically significant differences between tooth movement accuracies using optimized versus conventional attachments for either rotation or extrusion. The mean achieved values were all smaller than the predicted values for all attachment types and movements and this was statistically significant. For extrusion, the mean difference between predicted and achieved movements was clinically significant. Overall, the mean accuracy was 57.2%. The mean accuracy for extrusion was 47.6% and for rotation was 63.2%.

3.6 3M Clarity Clear Aligners

A cohort study by Grunheid et al. evaluated the orthodontic treatment efficacy of the 3M Clarity Aligner system using the Peer Assessment Rating (PAR) index and the American Board of Orthodontics Cast-Radiograph Evaluation (CR-Eval). Their results showed that the treatment reduced the CR-Eval scores from 39.05 ± 14.98 to 30.34 ± 8.76, resulting in a statistically significant difference of 8.76 ± 11.45 between pretreatment and posttreatment scores.

Invisalign was developed 20 years ahead of other competing clear aligner systems; therefore, there is more literature on these aligners than any other aligner system available. There are no present studies evaluating the specific efficacy of tooth movement with 3M Clarity Aligners as seen with Invisalign studies. There are no present studies comparing the efficacy of tooth movements between two aligner systems.

4.0 Purpose of Present Investigation

The purpose of this study is to determine whether there is a difference in the most common movement required in the refinement stage for Invisalign versus 3M Clarity Aligner System. This study aims to provide a side-by-side comparison of cases with Class I malocclusions treated with either Invisalign or the 3M Clarity™ Clear Aligner System before starting their respective refinement stage.

The null hypothesis of this study is that there is no difference in the most common movement required in the refinement stage for Invisalign or 3M Clarity Clear Aligners. The alternative hypothesis is that there is a difference in the most common movement required in the refinement stage for Invisalign or 3M Clarity Clear Aligners.

5.0 Materials and Methods

5.1 Overview

The University of Pittsburgh School of Dental Medicine Department of Orthodontics and Dentofacial Orthopedics will serve as the only source for participants. This study was reviewed by the University of Pittsburgh Institutional Review Board (IRB) and approved on December 12, 2022 to be effective December 12, 2022 (STUDY22080051).

5.2 Eligibility Criteria

Inclusion criteria for this study are patients with the following: all patients received treatment in both arches, all participants successfully completed an initial series of aligners without any pauses or restarts, patient charts indicated good compliance with consistent aligner wear, minimal movement of the molars in all 3 planes was planned, and treatment started in 2020 or later.

The exclusion criteria will include the noncompletion of the initial series of aligners, poor compliance, posterior crossbite, missing first or second molars, and anterior open bite.

5.3 Recruitment and Consent

Patients who met the eligibility criteria that were recruited have already completed one series of clear aligner therapy at the University of Pittsburgh School of Dental Medicine

Department of Orthodontics and Dentofacial Orthopedics. This retrospective study included patients within the last three years (2021-2023) who were treated amongst eight different orthodontic residents with similar orthodontic residency background training. There were no specific indications for which patient was treated with which modality as it was selected by random.

5.4 Study Design

1. Initial, Predicted, and Achieved scans all obtained (20 patients Invisalign and 20 patients 3M Clarity Clear Aligners).
2. Initial, predicted, and achieved digital models were imported into 3D Slicer.
3. The predicted and achieved models were superimposed over the initial ones with regional superimpositions on molars that appeared relatively stable in ClinCheck.
4. The central pits, or a reproducible area, of the first and second molars were marked, and a fiducial registration was performed for the model superimpositions.
5. The total number of teeth measured was 800.
6. For every subject, 112 measurements were made (56 predicted and 56 achieved movements) for horizontal movements, vertical movements, rotations, and transverse changes.
7. Horizontal displacements (parallel to the occlusal plane) were measured with the ruler tool at the middle of the incisal edges or cusp tips when the models were viewed directly from the occlusal view.
8. Vertical displacements were measured at the middle of the incisal edges or cusp tips.

9. Intercanine and interpremolar widths were measured at the canine cusp tips and the central grooves or central fossae (depending on the anatomic variation) of the second premolars.
10. Mesiodistal rotations were measured by tracing 2 points on the incisal edges of the incisors: the most mesial and most distal points of the canines and the labial and lingual cusp tips of the premolars. The 2 points were connected on each model with a straight line, and then the angle between the lines was measured on the horizontal plane.

5.5 Sample Size

Sample size calculation was based on previous studies using an average of 20 patients that met the inclusion and exclusion criteria. Our study included 73 patients that were recruited. 31 of those patients ended up being excluded from the study because they didn't meet all of the inclusion criteria.

5.6 Data Acquisition

Initial, predicted, and achieved scans were all obtained from the 20 patients that were treated with Invisalign and the 20 patients that were treated with 3M Clarity Clear Aligners. Initial, predicted, and achieved digital models were imported into the software 3D Slicer. 3D Slicer is a free, open-source software for visualization and image analysis. The predicted and achieved models were superimposed over the initial ones with regional superimpositions on molars that appeared relatively stable in the online prescription and ClinCheck. The central pits, or a

reproducible area, of the first and second molars were marked, and a fiducial registration was performed for the model superimpositions.

Maxillary and mandibular arches were superimposed and measured separately. The total number of teeth measured was 800. For every subject, 112 measurements were made (56 predicted and 56 achieved movements) for horizontal movements, vertical movements, rotations, and transverse changes. Horizontal displacements (parallel to the occlusal plane) were measured with the ruler tool at the middle of the incisal edges or cusp tips when the models were viewed directly from the occlusal view. Vertical displacements were measured at the middle of the incisal edges or cusp tips. Intercanine and interpremolar widths were measured at the canine cusp tips and the central grooves or central fossae of the second premolars. Mesiodistal rotations were measured by tracing two points on the incisal edges of the incisors: the most mesial and most distal points of the canines and the labial and lingual cusp tips of the premolars. The two points were connected on each model with a straight line, and then the angle between the lines was measured on the horizontal plane.

5.7 Statistical Analysis

Each tooth movement was measured separately and then the teeth were grouped together as follows to reduce the number of variables: contralateral teeth, first and second premolars, and mandibular central and lateral incisors. Vertical movement of the incisors was divided into intrusion and extrusion based on the predicted movement. Descriptive statistics were calculated for each movement. Wilcoxon signed-rank test was used to evaluate Invisalign and 3M patients separately because the data distribution was not normal. The Wilcoxon sum-rank test was used to

compare Invisalign patients with 3M patients. The level of significance for evaluating Invisalign separate from 3M was set at 0.05. The level of significance was set at 0.002 after applying the Bonferroni adjustment to control for type I error when comparing Invisalign versus 3M. The power for the movement with the smallest sample size (n = 20) was 95%.

6.0 Results

6.1 Group characteristics

A total of 71 patients were recruited. 31 of those patients were excluded from the study because they violated the inclusion criteria. A total of 40 patients were included in the study with 20 of those patients treated with Invisalign and 20 of those patients treated with 3M Clarity Clear Aligners. For every subject, 112 measurements were made (56 predicted and 56 achieved movements) for horizontal movements, vertical movements, rotations, and transverse changes. This totaled to 4,480 measurements performed in 3D Slicer for the present study.

6.2 Overview of predicted and achieved tooth movements presented for Invisalign

Table I shown here shows the Descriptive statistics of the predicted and achieved tooth movements for patients treated with Invisalign. A negative sign indicates that the opposite movement was observed, which is extrusion. Table 1 shows overall that there is a trend that the mean and median values for the predicted tooth movements were greater than the mean and median values for the achieved tooth movements for Invisalign patients. The most noticeable differences

between the predicted and achieved means and medians of tooth movements would be for the maxillary central incisor rotation and mandibular canine rotation.

Table 1: Descriptive statistics of the predicted and achieved tooth movements presented for Invisalign

		Predicted			Achieved		
Movement	n	Mean	Median	SD	Mean	Median	SD
Max central incisors horizontal (mm)	40	1.74	1.30	1.48	1.63	1.21	1.43
Max lateral incisors horizontal (mm)	40	1.59	1.67	1.11	1.62	1.34	1.09
Max canines horizontal (mm)	40	0.96	0.51	1.02	0.97	0.77	0.75
Max central incisors intrusion (mm)	34	0.47	0	0.79	0.21	0	0.32
Max central incisors extrusion (mm)	46	-0.87	-0.44	1.10	-1.26	-0.39	1.68
Max lateral incisors intrusion (mm)	22	0.28	0	0.68	0.33	0	0.60
Max lateral incisors extrusion (mm)	58	-1.46	-1.28	1.29	-1.39	-1.38	1.42
Max canines vertical (mm)	40	-0.45	-0.91	1.77	-0.55	-0.25	1.18
Max intercanine width change (mm)	20	0.92	0.67	1.27	0.92	0.49	1.21
Max interpremolar width change (mm)	20	1.28	0.91	1.07	0.84	0.57	0.67
Max central incisors rotation (^{o})	40	11.68	11.30	6.62	6.10	5.43	3.42
Max lateral incisors rotation (^{o})	40	16.94	15.43	11.46	10.00	8.38	5.69
Max canines rotation (^{o})	40	9.89	9.13	4.19	6.98	6.43	4.03
Max premolars rotation (^{o})	80	7.48	5.50	5.69	3.72	3.77	1.36
Man incisors horizontal (mm)	80	1.49	0.70	1.50	1.62	1.23	1.32
Man canines horizontal (mm)	40	1.47	1.25	1.00	1.24	0.98	0.87
Man incisors intrusion (mm)	156	2.13	2.09	1.03	1.35	1.15	0.99
Man incisors extrusion (mm)	4	0	0	0	-0.06	0	0.28
Man canines vertical (mm)	40	1.29	1.55	1.20	0.95	0.91	0.96
Man premolars vertical (mm)	80	0.67	0.58	0.72	0.32	0.47	0.91
Man intercanine width change (mm)	20	1.66	1.60	1.05	1.24	1.18	0.82
Man interpremolar width change (mm)	20	1.29	1.19	0.91	0.97	0.90	0.93
Man incisors rotation (^{o})	80	17.27	16.99	8.82	12.55	12.00	6.63
Man canines rotation (^{o})	40	20.75	19.18	9.64	10.30	9.45	5.70
Man premolars rotation (^{o})	80	8.17	8.66	3.18	5.07	3.60	4.91
A negative sign indicates that the opposite movement was observed (extrusion).							

6.3 Overview of predicted and achieved tooth movements presented for 3M Clarity Aligners

Table II shows the results from the Descriptive statistics of the predicted and achieved tooth movements for patients treated with 3M Clarity Aligners. are presented in Table II. Again, a negative sign indicates that the opposite movement was observed, which is extrusion. Overall, you can see a trend that the mean and median values for the predicted tooth movements were greater than the mean and median values for the achieved tooth movements for 3M Clarity Aligner patients. The most noticeable differences between the predicted and achieved means and medians of all the tooth movements would be the maxillary lateral incisor extrusion and mandibular canine rotation.

Table 2: Descriptive statistics of the predicted and achieved tooth movements presented for 3M Clarity Aligners

		Predicted			Achieved		
Movement	n	Mean	Median	SD	Mean	Median	SD
Max central incisors horizontal (mm)	40	1.00	0.91	0.64	0.76	0.70	0.59
Max lateral incisors horizontal (mm)	40	0.89	0.63	0.60	0.76	0.63	0.58
Max canines horizontal (mm)	40	0.90	0.83	0.62	0.72	0.44	0.88
Max central incisors intrusion (mm)	48	0.74	0.54	0.71	0.56	0.15	0.80
Max central incisors extrusion (mm)	32	-0.08	0	0.41	-0.29	0	1.01
Max lateral incisors intrusion (mm)	40	0.51	0.14	0.70	0.42	0	0.59
Max lateral incisors extrusion (mm)	40	-0.12	0	0.93	-0.64	-0.16	1.09
Max canines vertical (mm)	40	0.23	0.51	1.16	0.26	0.53	1.11
Max intercanine width change (mm)	20	0.88	0.76	0.56	0.71	0.65	0.58
Max interpremolar width change (mm)	20	1.07	0.69	0.84	0.93	0.96	0.64
Max central incisors rotation (°)	40	14.27	11.68	8.62	12.92	9.83	9.78
Max lateral incisors rotation (°)	40	17.02	14.50	10.18	12.77	7.95	12.51
Max canines rotation (°)	40	14.12	9.93	12.00	8.06	6.33	6.20
Max premolars rotation (°)	80	6.36	5.73	3.14	4.78	3.77	2.59
Man incisors horizontal (mm)	80	1.38	1.03	1.21	1.16	0.85	1.11
Man canines horizontal (mm)	40	1.05	0.79	0.96	0.95	0.49	1.02
Man incisors intrusion (mm)	136	1.72	1.72	1.34	1.08	0.59	1.37
Man incisors extrusion (mm)	24	-0.06	0	0.25	-0.23	0	0.61
Man canines vertical (mm)	40	1.25	1.05	1.13	0.62	0.44	1.46
Man premolars vertical (mm)	80	0.42	0.55	0.72	0.43	0.28	0.82
Man intercanine width change (mm)	20	0.95	0.89	0.77	1.02	0.87	0.79
Man interpremolar width change (mm)	20	1.42	1.22	1.28	0.90	0.72	0.74
Man incisors rotation (°)	80	18.66	17.91	9.69	14.54	14.80	7.73
Man canines rotation (°)	40	21.09	18.80	11.09	12.66	13.28	7.70
Man premolars rotation (°)	80	8.01	6.99	4.93	5.34	4.19	3.40
A negative sign indicates that the opposite movement was observed (extrusion).							

6.4 Accuracy of each movement for Invisalign

Table III here shows the results of the Wilcoxon signed-rank tests between predicted and achieved measurements that were performed to assess the accuracy of each movement for patients treated with Invisalign. A negative value indicates that the achieved values were greater than the

predicted ones. Overall, horizontal movements of all incisors seemed to be accurate, with differences either small (0.09-0.53 mm) or insignificant. Extrusion of incisors also appeared to be accurate, since no statistically significant differences were observed. As far as intrusion goes for the incisors, intrusion of the mandibular incisors was the most inaccurate of all linear movements. The mandibular incisors had the greatest difference of 0.94 mm ($P \leq 0.05$). The vertical for both Maxillary and mandibular canines and premolars were accurate.

The horizontal movements of the canines seemed to be accurate for both the maxilla and mandible. That was also reflected by the intercanine width change in the maxilla only. Intercanine expansion in the mandible was not accurate, making this statistically significant. Interpremolar expansion was not accurate for both arches, making this statistically significant as well. For rotations, the findings were statistically significant for all teeth, except the maxillary canines. The laterals had the greatest discrepancies of 5.87 in the maxillary arch and the canines had the greatest discrepancy of 9.73 in the mandibular arch. The maxillary premolars had the lowest discrepancy of only 1.73.

Table 3: Results of the Wilcoxon signed-rank tests between predicted and achieved measurements performed to assess the accuracy of each movement for Invisalign.

Movement	Median predicted	Median difference (predicted – achieved)	P value
Max central incisors horizontal (mm)	1.30	0.09	0.7652
Max lateral incisors horizontal (mm)	1.67	0.33	0.8813
Max canines horizontal (mm)	0.51	-0.26	0.4553
Max central incisors intrusion (mm)	0	0	0.3941
Max central incisors extrusion (mm)	-0.44	0.05	0.4397
Max lateral incisors intrusion (mm)	0	0	0.4970
Max lateral incisors extrusion (mm)	-1.28	0.10	0.5005
Max canines vertical (mm)	-0.91	-0.66	0.6541
Max intercanine width change (mm)	0.67	0.18	0.8813
Max interpremolar width change (mm)	0.91	0.34	0.0276*
Max central incisors rotation (^{o})	11.30	5.87	0.0019*
Max lateral incisors rotation (^{o})	15.43	7.05	0.0111*
Max canines rotation (^{o})	9.13	2.7	0.0569
Max premolars rotation (^{o})	5.50	1.73	0.0015*
Man incisors horizontal (mm)	0.70	-0.53	0.8519
Man canines horizontal (mm)	1.25	0.27	0.1850
Man incisors intrusion (mm)	2.09	0.94	0.0022*
Man incisors extrusion (mm)	0	0	0.3173
Man canines vertical (mm)	1.55	0.64	0.1354
Man premolars vertical (mm)	0.58	0.11	0.3703
Man intercanine width change (mm)	1.60	0.42	0.0169*
Man interpremolar width change (mm)	1.19	0.29	0.0095*
Man incisors rotation (^{o})	16.99	4.99	0.0025*
Man canines rotation (^{o})	19.18	9.73	0.0001*
Man premolars rotation (^{o})	8.66	5.06	0.0015*
A negative sign indicates that the achieved value was greater than the predicted one. *Statistically significant difference ($P \leq 0.05$).			

6.5 Accuracy of each movement for 3M Clarity Aligners

Table IV here shows the results of the Wilcoxon signed-rank tests between predicted and achieved measurements that were performed to assess the accuracy of each movement for patients treated with 3M. Again, a negative value indicates that the achieved values were greater than the

predicted ones. Overall, horizontal movements of all incisors seemed to be accurate, with differences either small (0.00-0.21 mm) or insignificant. When looking at extrusion, the extrusion of the maxillary lateral incisors was the most inaccurate with a P value of 0.0093. As far as intrusion goes for the incisors, intrusion of the mandibular incisors was the most inaccurate of all linear movements. The mandibular incisors had the greatest difference of 1.13 mm with a P value less than 0.05. Vertical canine movement was predictable in both maxillary and mandibular arches. Vertical movement of the mandibular first premolars did not show a significant discrepancy, but the median planned movement was low at 0.27 mm.

The horizontal movements of the canines seemed to be accurate for both the maxilla and mandible. That was also reflected by the intercanine width change. Interpremolar expansion was accurate for the maxillary arch but not accurate for the mandibular arch, making this statistically significant. For rotations, the findings were statistically significant for all teeth, except the maxillary central incisors and maxillary premolars. The laterals had the greatest discrepancies of 6.55 in the maxillary arch and the canines had the greatest discrepancy of 5.52 in the mandibular arch. The mandibular premolars had the lowest discrepancy of only 2.80.

Table 4: Results of the Wilcoxon signed-rank tests between predicted and achieved measurements performed to assess the accuracy of each movement for 3M Clarity Aligners.

Movement	Median predicted	Median difference (predicted – achieved)	P value
Max central incisors horizontal (mm)	0.91	0.21	0.2706
Max lateral incisors horizontal (mm)	0.63	0	0.2958
Max canines horizontal (mm)	0.83	0.39	0.0793
Max central incisors intrusion (mm)	0.54	0.39	0.1650
Max central incisors extrusion (mm)	0	0	0.2781
Max lateral incisors intrusion (mm)	0.14	0.14	0.4215
Max lateral incisors extrusion (mm)	0	0.16	0.0093*
Max canines vertical (mm)	0.51	-0.02	0.9108
Max intercanine width change (mm)	0.76	0.11	0.4221
Max interpremolar width change (mm)	0.69	-0.27	0.3135
Max central incisors rotation (^{o})	11.68	1.85	0.6542
Max lateral incisors rotation (^{o})	14.50	6.55	0.0169*
Max canines rotation (^{o})	9.93	3.60	0.0152*
Max premolars rotation (^{o})	5.73	1.96	0.0859
Man incisors horizontal (mm)	1.03	0.18	0.2043
Man canines horizontal (mm)	0.79	0.30	0.6813
Man incisors intrusion (mm)	1.72	1.13	0.0038*
Man incisors extrusion (mm)	0	0	0.2805
Man canines vertical (mm)	1.05	0.61	0.0620
Man premolars vertical (mm)	0.55	0.27	0.7651
Man intercanine width change (mm)	0.89	0.02	0.4115
Man interpremolar width change (mm)	1.22	0.50	0.0036*
Man incisors rotation (^{o})	17.91	3.37	0.0028*
Man canines rotation (^{o})	18.80	5.52	0.0032*
Man premolars rotation (^{o})	6.99	2.80	0.0022*
A negative sign indicates that the achieved value was greater than the predicted one. *Statistically significant difference ($P \leq 0.05$).			

6.6 Invisalign versus 3M Clarity Aligners

The Wilcoxon sum-rank test was used to compare Invisalign patients with 3M patients to answer our main research question, which was investigating if there is a difference in the most

inaccurate tooth movements between two clear aligner systems. The level of significance was set at 0.002 after applying the Bonferroni adjustment to control for type I error when comparing Invisalign versus 3M.

When looking the results in Table 5 shown, it shows that there are no statistically significant differences between any of the tooth movements when comparing Invisalign with 3M Clarity Aligners. All tooth movements have a P value that is greater than 0.002. Therefore, we can accept our null hypothesis and say that there are no differences in the most inaccurate tooth movements between two clear aligner systems.

Table 5: Results of the Wilcoxon rank-sum tests comparing Invisalign with 3M Clarity Aligners.

Movement	Number of Comparisons	P value for Comparison
Max central incisors horizontal (mm)	80	0.7868
Max lateral incisors horizontal (mm)	80	0.6553
Max canines horizontal (mm)	80	0.0659
Max central incisors intrusion (mm)	82	0.5283
Max central incisors extrusion (mm)	78	0.9451
Max lateral incisors intrusion (mm)	62	0.2767
Max lateral incisors extrusion (mm)	98	0.0404
Max canines vertical (mm)	80	0.5338
Max intercanine width change (mm)	40	0.6167
Max interpremolar width change (mm)	40	0.2184
Max central incisors rotation (^{o})	80	0.0360
Max lateral incisors rotation (^{o})	80	0.7251
Max canines rotation (^{o})	80	0.6456
Max premolars rotation (^{o})	160	0.2447
Man incisors horizontal (mm)	160	0.2793
Man canines horizontal (mm)	80	0.4328
Man incisors intrusion (mm)	292	0.9784
Man incisors extrusion (mm)	28	0.6046
Man canines vertical (mm)	80	0.4989
Man 1st premolars vertical (mm)	160	0.5885
Man intercanine width change (mm)	40	0.0326
Man interpremolar width change (mm)	40	0.6263
Man incisors rotation (^{o})	160	0.8817
Man canines rotation (^{o})	80	0.6652
Man premolars rotation (^{o})	160	0.3507
*Statistically significant difference ($P \leq 0.05$).		

7.0 Discussion

To be able to interpret the results accurately, limitations of this study should be discussed first. The risk of selection bias could not be prevented because this was a retrospective study. All of the participants were treated with either Invisalign or 3M Clarity Clear Aligners by eight orthodontic residents who have a similar orthodontic background but may tend to treatment plan aligner cases differently due to different assigned faculty to each case. Some patients alternated between 7 days, 10 days, and 2-week intervals of changing their clear aligner trays, which eludes to the argument that retrospective studies may not be able to control patient cooperation.

Superimpositions were done on first and second molar teeth, which were assumed to be stable when looking at the online prescriptions. Consequently, any movements detected were relative to the molars. One way to overcome this superimposition obstacle would be to take a cone-beam computed tomography and perform a cranial-base superimposition. This would help allow accurate measurements of the achieved movements. However, this would have not worked for the for the predicted movements, and those measurements would still be needed with an online prescription.

Although the evidence is unclear, there is a possibility that interproximal reduction and attachments may impact tooth movement accuracy. There are also varying factors between the Invisalign and 3M Clarity Clear Aligner systems which include attachment design and style, thickness of aligner material, and scalloped versus straight edge design of the trays. All measurements for Invisalign and 3M Clarity Clear Aligners were done at the incisal edges, and buccolingual and mesiodistal tipping and torque were not studied. Translation and tipping are described with a subjective center of rotation and it’s possible that the movements were expressed

differently than predicted (ie, more tipping than translation); therefore, this would show shifts of the incisal edge.

Another limitation includes the intra-radar reliability. Reliability was not assessed 1 month after the initial measurements. Previous studies had the same examiner remeasure about 10% of the subjects to confirm intra-radar reliability. The last but most important limitation of this study is that multiple teeth were used from the same patient. The movement of one tooth is not independent from the movement of adjacent teeth or the ones that are used as anchorage (Kravitz et al. 2009). The ideal way to overcome this limitation would have been to include only one movement of one tooth from every patient, but this would require a larger sample to be recruited.

When evaluating the results in the horizontal, we failed to detect any major differences between predicted and achieved movements in the horizontal plane for Invisalign patients. The greatest difference was found in the mandibular intercanine width change (0.42 mm), which was statistically significant. Mandibular intercanine and maxillary and mandibular interpremolar expansions were inaccurate and statistically significant. For 3M Clarity Clear Aligner patients, we failed to detect any major differences between predicted and achieved movements in the horizontal plane. The greatest difference was found in the mandibular interpremolar width change (0.50 mm), which was statistically significant. Maxillary and mandibular intercanine, and maxillary interpremolar width expansions were accurate and not statistically significant. Previous studies found no difference between predicted and achieved movements in the horizontal plane. The greatest difference was found in the maxillary intercanine width change and their reasoning was because the maxillary canines have the longest roots and conical crown morphology with few undercuts to enhance aligner retention (Kravitz et al., 2009).

When evaluating the results in the vertical, mandibular incisor intrusion was the most unpredictable for Invisalign patients. For 3M Clarity Clear Aligner patients, maxillary lateral incisor extrusion and mandibular incisor intrusion was the most unpredictable. For some of the intrusion measurements, especially for the maxillary central and lateral incisors, even though the planned movement was intrusion, the achieved movement was extrusion. Previous studies show intrusion was the most unpredictable, with linear movements ranging from 0.8 to 1.5 mm. (Kravitz et al., 2009). Achieving extrusion instead of intrusion may appear to be a flaw but this finding is important to this study because the extrusion of incisors relative to the molars could have clinical significance. The biteblock effect may make deepbites more difficult to treat with Invisalign (Kravitz et al., 2009).

When evaluating the rotations, all achieved rotations were significantly smaller than the predicted ones by different amounts for Invisalign patients. The median differences ranged from 1.73 to 9.73. The most unpredictable teeth were the rotations of the mandibular canines. For 3M Clarity Clear Aligner patients, all achieved rotations were significantly smaller than the predicted ones by different amounts. The median differences ranged from 1.85 to 6.55. The most unpredictable teeth were the rotations of the maxillary lateral incisors, which is different than the results of Invisalign and previous studies. Previous studies showed that all achieved rotations were significantly smaller than the predicted ones by different amounts. The median differences ranged from 0.9 to 3.05. Their rotations of the maxillary and mandibular canines were the most unpredictable of all anterior teeth.

There were no statistically significant differences found between any of the tooth movements when comparing Invisalign with 3M Clarity Aligners. The level of significance was set at 0.002, which means we accept our null hypothesis stating that there is no difference in the

most inaccurate tooth movements between two clear aligner systems. If we didn't apply the Bonferroni adjustment to control for type I error, the level of significance would have been set to 0.05 and we would have rejected the null hypothesis stating there was found to be a difference in the most inaccurate tooth movements between two clear aligner systems, which were found to be the maxillary lateral incisor extrusion, maxillary central incisor rotation, and mandibular intercanine width change.

This study chose to focus on the size of the difference between the predicted and achieved movements instead expressing the accuracy of clear aligners in percentages like previous studies have done. This is because a percentage gives less information about the movements that were studied and the differences that were found. Most previous studies were published before the introduction of the SmartTrack material and the latest attachments as well as software updates. The hope is that this study offers some valuable evidence regarding the accuracy of two clear aligner companies in their current versions individually and how they compare with each other.

8.0 Future Research

Future research can focus on recruiting more patients and observing the most common movements needed past the first refinement stage for clear aligner therapy. Orthodontists report a high percentage of patients requiring one or more refinement stages to full correct patients' malocclusions. This is due to the unpredictability of what tooth movements are the most difficult to achieve. Practitioners would be able to plan in their prescriptions to overcorrect certain tooth movements that are harder to accomplish with aligners to guarantee that the movements will take place successfully. This may not decrease the length of treatment time in total but would help limit the down time in between waiting for the patient's new refinement aligners.

Another research project can explore comparing other clear aligner systems that are available for practitioners. They all have similar concepts in moving teeth but differ in tray shape, tray size, attachment style, and biomechanics. If we're able to know which tooth movements are easier to control with what clear aligner system, we can coordinate specific systems for specific patients that we see in our practice.

9.0 Conclusions

1. Mandibular intercanine width expansion was the most inaccurate in the horizontal for Invisalign. Mandibular interpremolar width expansion was the most inaccurate in the horizontal for 3M Clarity Aligners.
2. Mandibular incisor intrusion was the most inaccurate movement in the vertical for both Invisalign and 3M Clarity Aligners.
3. Regarding rotations, the most inaccurate teeth for Invisalign were the mandibular canines and the most inaccurate teeth for 3M Clarity Aligners were the maxillary incisors.
4. There were no statistically significant differences found between any of the tooth movements when comparing Invisalign with 3M Clarity Aligners. Even though there weren't any statistical significances comparing the two aligner systems, Invisalign was more accurate in achieving maxillary lateral extrusion and 3M Clarity Aligners was more accurate in achieving maxillary central incisor rotation and mandibular intercanine width change.

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