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Accuracy and Variability of Maxillary Lateral Incisor Movements with Optimised and Conventional Attachments in Clear Aligner Therapy (CAT): A Retrospective Cohort Study

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Abstract

Objective

Evaluate the accuracy and variability of predicted versus achieved maxillary lateral incisor movements with optimised and conventional attachments in CAT.

Methods

This retrospective cohort study included 56 patients (90 lateral incisors; 46 conventional; 44 optimised) treated with Invisalign Lite. Predicted and achieved movements were assessed using 3D superimposition for three linear (mesiodistal, buccolingual, occlusogingival) and three angular (tip, torque, rotation) parameters. Prediction error (one-sample t-tests), between-group comparisons (linear mixed-effects models), and clinical equivalence (two one-sided tests, TOST) with predefined margins (± 0.25 mm and ± 0.5°) were calculated.

Results

Torque (mean difference of 1.07°; SD 4.06, 90% CI: 0.37 to 1.78, p = 0.013) indicated reduced expression. Other parameters showed smaller mean differences (mesiodistal − 0.08 mm, buccolingual − 0.08 mm) and notable variability (SD 6.25° for rotation). Within-group discrepancies were observed in occlusogingival (0.25 mm, SD 0.40) and rotational (1.95°, SD 5.28) movements in the conventional group, and in buccolingual (− 0.22 mm, SD 0.55) and occlusogingival (− 0.17 mm, SD 0.47) movements in the optimised group. Between-group comparisons showed significant differences for buccolingual (− 0.21 mm, p = 0.040) and occlusogingival (− 0.42 mm, p < 0.001). Mesiodistal was the only parameter demonstrating clinical equivalence between groups (TOST p = 0.004). Dose–response analyses showed greater discrepancies across all parameters with increased planned movements.

Conclusions

Small mean discrepancies but considerable variability, particularly for angular movements, were noted. Mesiodistal movement showed clinically acceptable agreement between attachment types, while no consistent advantage of one attachment design was observed across all movements. Increased planned movement was associated with greater discrepancy.

Introduction

The advent of clear aligners has introduced intricate biomechanical challenges stemming from the distribution of forces across tooth surfaces, in marked contrast to fixed appliances that deliver forces at discrete points [1, 2]. Aligner-based tooth movement is facilitated by preprogrammed geometric alterations within the aligner, which create dynamic zones of relief and pressure. A critical biomechanical mechanism is the ‘shape moulding effect’, which is bolstered by auxiliary components such as attachments and power ridges. The efficacy of these attachments is influenced by factors including design, size, location, and active surface area [3, 4]. Attachments are broadly divided into two categories: conventional and optimised. Conventional attachments feature standardised dimensions and can be oriented in any direction based on the orthodontist’s clinical discretion; however, they are often limited by their performance across variable clinical scenarios. In contrast, optimised attachments are designed algorithmically and placed automatically within treatment planning software (ClinCheck). Existing research on optimised attachments across various tooth movements and malocclusions, including extrusion, rotation, overbite reduction, and open bite correction, remains incomplete. Nonetheless, modifications to these optimised designs during treatment are generally discouraged, leaving a gap in the literature regarding their specific efficacy [5, 6].

Maxillary lateral incisors pose unique challenges in orthodontic treatment protocols. Their reduced surface area, tapered crown morphology, and minimal anatomical undercuts often render them susceptible to inefficient force application from aligners, making them the “Achilles heel” of maxillary anterior aligner tracking [7]. Attachments aim to enhance the effective application of force by increasing the lateral incisors’ surface area. Despite the widespread use of optimised attachments, their specific impact on the predictability of maxillary lateral incisor movements, compared with conventional attachments, has not been quantified in non-extraction clear aligner therapy. Furthermore, previous studies have rarely applied equivalence testing to distinguish statistical from clinically meaningful differences.

Notably, there remains a lack of comparative studies directly evaluating treatment outcomes for conventional and optimised attachments [5, 6, 8, 9]. Quantifying the efficacy of these attachments using software superimposition is essential; it not only provides valuable insights into clinical strategies but also helps refine attachment design for improved outcomes.

The objective of this study was to compare the accuracy of maxillary lateral incisor movements with optimised versus conventional attachments in patients treated with Invisalign Lite on a non-extraction basis, using 3D model superimposition and equivalence testing. The null hypothesis was that there was no significant difference in the accuracy of maxillary lateral incisor movements between conventional and optimised attachment designs when using Invisalign Lite aligners for non-extraction orthodontic treatment.

Methods

Study design

This was a retrospective cohort study.

Setting

Treatment was delivered at a single private orthodontic practice in Dubai, United Arab Emirates (UAE), managed by a Diamond Apex Invisalign provider (WS). Patients were treated between 2021 and 2024, and data were collected retrospectively in 2024 from clinical records at the private practice in Dubai, UAE.

Ethical approval, consent and reporting

Ethical approval was obtained from the Scientific Review Board of Saveetha Dental College (SRB/SDC/PhD/ORTHO-2119/22/010). Written informed consent was obtained from all participants prior to treatment and for the use of their anonymised records in research. The study was reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for cohort studies.

Participants

Eligibility criteria

Participants were included if they:

1. completed non-extraction treatment using Invisalign Lite with a complete set of initial, predicted setup, and post-treatment records (scan after completion of 14 trays),
2. were in the permanent dentition with no missing teeth except third molars, and
3. had maxillary lateral incisors free of pathology, restorations, crowns, or veneers.
4. initial malocclusion with crowding less than 4mm

Participants were excluded if they:

1. underwent single-arch treatment,
2. completed treatment with fewer than 14 aligner trays, or
3. had power ridges and/or double attachments
4. underwent IPR (inter proximal reduction) and/or used intermaxillary elastics

Selection of participants and follow-up

Patients were identified retrospectively from the clinical database by treatment modality (Invisalign Lite) and time period (2021–2024). Records were screened for completeness of digital datasets, including initial scans, predicted ClinCheck models, and post-treatment intraoral scans. Treatment completion was defined as the end of the initial aligner series (14 aligners), and only these records were included in the analysis. Cases requiring refinement stages were excluded to ensure that the outcomes reflected the predictability of the initial treatment phase.

Outcomes (primary and secondary)

The primary outcome was the difference between predicted and achieved buccolingual movement of the maxillary lateral incisor. Buccolingual movement was chosen as the primary outcome for its clinical importance.

The secondary outcomes were the differences between predicted and achieved movements for the remaining parameters including mesiodistal and occlusogingival (linear movements) and tip, torque, and rotation (angular movements).

For all primary and secondary outcomes, prediction error was defined as the difference between predicted and achieved tooth movement (predicted – achieved) with positive values indicating greater planned movement than the achieved outcome.

Equivalence testing was conducted to assess whether the magnitude of prediction error fell within predefined clinically acceptable limits (± 0.25 mm for linear movements and ± 0.5° for angular movements), which represent thresholds for negligible discrepancies in digital orthodontic measurements.

Interventions (attachment design)

Two treatment groups were defined based on attachment design. In the conventional group, attachments were placed at the clinician's discretion. In the optimised group, attachment design and positioning were determined by ClinCheck software and then placed clinically according to the digital setup.

All patients were treated with a standardised aligner protocol (Invisalign Lite, 14 aligners) on a weekly wear schedule. The standard attachment bonding protocol was followed, including preloaded flowable composite (Filtek Supreme Flowable, 3M Dental, USA), cured for 3–5 seconds per attachment with a light-emitting diode (LED) curing light (VALO Ortho Cordless, American Orthodontics, United States).

Predictors and potential confounders

The primary predictor variable was attachment design (conventional vs optimised). Potential confounders included patient age, sex, treatment duration and initial malocclusion characteristics. Treatment conditions were standardised (single clinician, uniform aligner protocol) to minimise variability arising from performance factors. Patient compliance was assumed based on completion of the prescribed aligner series.

Data sources and measurement

Predicted tooth positions were obtained from the final ClinCheck setup, whereas achieved tooth positions were derived from post-treatment intraoral scans. All digital models were analysed using Compare software (Fig. 1) according to a standardised superimposition protocol described by Grunheid et al.[10]. Tooth movements were quantified across three linear (mesiodistal, buccolingual, occlusogingival) and three angular (tip, torque, rotation) dimensions. The outcome assessor (SM) was blinded to attachment group allocation.

Bias

Selection bias may have arisen because only patients who completed treatment with a full set of records were included, potentially excluding those with poor compliance, incomplete treatment or missing data. The number of excluded cases and the reasons for exclusion are presented in the participant flow diagram to allow transparent assessment of this potential bias. Performance bias was minimised by using a standardised treatment protocol, including a single clinician, a uniform aligner system (Invisalign Lite) and a consistent weekly wear schedule across all participants. Attrition bias was limited by including only completed cases with complete datasets. However, this approach may preferentially include patients with better compliance and treatment progression. Detection (measurement) bias was reduced by blinding the outcome assessor to attachment group allocation and by applying a standardised digital superimposition protocol. Intra-examiner reliability assessment demonstrated high reproducibility of measurements, thereby supporting the consistency of outcome assessment. Reporting bias was minimised by analysing and reporting all pre-specified primary and secondary outcomes without selective omission.

Sample size calculation

Sample size calculation was based on buccolingual movement as the reference outcome, using estimates from pilot data. A between-group difference of 0.29 mm and a pooled standard deviation of 0.46 mm were assumed, with a two-sided significance level of 0.05 and 80% power. This yielded an unadjusted requirement of 40 teeth per group (80 teeth in total). As maxillary lateral incisors are clustered within participants, the sample size was adjusted using a design effect based on an anticipated mean cluster size of 1.62 teeth per participant and an intraclass correlation coefficient of 0.19. The mean cluster size represents the average number of eligible teeth per participant in the pilot dataset. It is expressed as a decimal because not all participants contribute two lateral incisors. The resulting design effect was 1.12, increasing the required sample size to 90 teeth. The final analysed sample comprised 90 maxillary lateral incisors contributed by 56 participants.

Quantitative variables

Tooth movements were measured as continuous variables in millimetres (linear) and degrees (angular). The parameters assessed were mesiodistal, buccolingual, occlusogingival, tip, torque and rotation.

Statistical Analysis

All statistical analyses were conducted in SPSS (version 23.0). Data normality was assessed using the Shapiro–Wilk test. Predicted and achieved tooth movements were evaluated for three linear (mesiodistal, buccolingual and occlusogingival) and three angular (tip, torque and rotation) parameters. For each parameter, a difference score (predicted – achieved) was calculated, with positive values indicating greater planned movement than achieved. The mean difference from zero was assessed using one-sample t-tests for the overall sample and within each attachment group separately. Clinical equivalence between predicted and achieved movements was evaluated using the two one-sided tests (TOST) procedure.

To account for the hierarchical structure of the data (teeth nested within patients), linear mixed-effects models were fitted using restricted maximum likelihood (REML) estimation. In these models, the difference score was specified as the dependent variable, attachment group as a fixed effect and patient as a random intercept. This approach accounted for within-patient clustering and adjusted standard errors accordingly.

The intraclass correlation coefficient (ICC) was derived from the variance components of the mixed models to quantify the proportion of variance attributable to between-patient variation.

Equivalence testing using TOST was also applied to the between-group fixed effects, with predefined equivalence margins of ± 0.25 mm for linear movements and ± 0.5° for angular movements consistent with thresholds reported for clinically negligible discrepancies in digital orthodontic measurements [11, 12].

Exploratory confounder-adjusted analyses were performed using models adjusted for age, sex and the magnitude of planned movement. To further evaluate the relationship between treatment complexity and outcome, dose–response analyses were conducted using linear regression models to assess associations between the magnitude of planned movement and (1) signed prediction error (directional accuracy) and (2) absolute prediction error (magnitude of discrepancy). These models were adjusted for age, sex and attachment group.

Each movement parameter was analysed separately to capture distinct biomechanical outcomes. However, the potential interdependence among movement components was taken into account when interpreting the results. Given the evaluation of multiple outcomes, the findings were interpreted with due consideration of multiple comparisons and the potential for type I error. Statistical significance was set at $p < 0.05$.

Results

Participant flow

A total of 63 patients treated between 2021 and 2024 met the eligibility criteria and were included in the analysis. The final sample comprised 56 patients contributing 90 maxillary lateral incisors of which 46 received conventional attachments and 44 received optimised attachments. Only cases that completed the initial aligner series with complete datasets were analysed. A detailed participant flow diagram is provided (Fig. 2).

Baseline data

Baseline characteristics by attachment group are presented in Table 1. In the conventional attachment group, 46 maxillary lateral incisors were analysed, with a mean age of 35.1 ± 6.7 years; 17 (37%) were from male patients and 29 (63%) from female patients. In the optimised attachment group, 44 maxillary lateral incisors were analysed, with a mean age of 33.8 ± 6.1 years; 13 (29.5%) were from male patients and 31 (70.5%) from female patients. The magnitude of planned movements was limited (< 0.8 mm for linear and < 8° for angular movements), reflecting the treatment scope of Invisalign Lite.

Table 1
Baseline characteristics by attachment group

Demographic variable	Conventional attachment group	Optimised attachment group
Lateral incisors analysed*, n	46	44
Age, mean ± SD (years)	35.1 ± 6.7	33.8 ± 6.1
Male, n (%)	17 (37)	13 (29.5)
Female, n (%)	29 (63)	31 (70.5)
*Since attachment allocation was performed at the tooth level, baseline characteristics are presented according to the analysed lateral incisors.		

Sample analysed

All 90 maxillary lateral incisors were included in the analysis. Because multiple teeth were contributed by individual patients, the hierarchical structure of the data (teeth nested within patients) was accounted for using linear mixed-effects models with patients specified as a random effect. No missing outcome data were observed. The distribution of observations per patient was consistent with bilateral representation in a subset of cases and clustering was formally accounted for in all between-group analyses.

Outcome data (Primary and secondary outcomes)

Across all 90 lateral incisors, the differences between predicted and achieved movements were small in magnitude but showed notable variability across movement types (Table 2). Torque showed a statistically significant mean difference of 1.07° (SD 4.06, 90% CI: 0.37 to 1.78, p = 0.013), indicating that the achieved movement was less than predicted (Table 2). No other movement parameters showed statistically significant differences. Mesiodistal (− 0.08 mm, SD 0.38), buccolingual (− 0.08 mm, SD 0.48) and occlusogingival (0.04 mm, SD 0.48) movements showed minimal mean discrepancies. However, the associated variability and confidence intervals indicate dispersion around the mean (Table 2). Angular movements, particularly rotation (SD 6.25°) and tip (SD 4.42°), showed greater variability (Table 2). None of the six movement parameters met the predefined criteria for clinical equivalence (Table 2).

Table 2

Overall Predictability of Lateral Incisor Movements using One-sample t-test (H_0: mean difference = 0) and clinical equivalence using TOST equivalence tes

Movement	Unit	Predicted Mean	Predicted SD	Achieved Mean	Achieved SD	Difference Mean	Difference SD	90% CI Lower	90% CI Upper	p-value (t-test)	TOST p-value	Cor
Mesiodistal	mm	-0.120	0.410	-0.041	0.292	-0.079	0.381	-0.145	-0.0127	0.051	1.000	Not Not Equ
Buccolingual	mm	0.059	0.491	0.143	0.513	-0.084	0.477	-0.167	-0.0008	0.097	1.000	Not Not Equ
Occlusogingival	mm	0.254	0.475	0.213	0.281	0.040	0.481	-0.043	0.1242	0.428	1.000	Not Not Equ
Tip	Degree(°)	-0.072	4.233	0.113	3.197	-0.186	4.418	-0.955	0.5837	0.689	0.929	Not Not Equ
Torque	Degree(°)	0.276	4.159	-0.795	3.273	**1.071**	4.056	0.365	1.7787	**0.013***	1.000	Sta Not Equ
Rotation	Degree(°)	2.039	6.886	1.030	2.706	1.009	6.254	-0.080	2.0986	0.127	0.988	Not Not Equ

** p < 0.05 (statistically significant). ! Shapiro–Wilk p < 0.05 (non-normal distribution; parametric tests applied under central limit theorem, n ≥ 45). Equivalence ma ±0.25 mm (linear movements); ±0.5° (angular movements). TOST p < 0.05 = clinically equivalent. Difference = Predicted − Achieved. Positive difference = overesti by software.*

Within-group analyses

In the conventional attachment group (n = 46 teeth), occlusogingival movement showed a mean difference of 0.25 mm (SD 0.40, 90% CI: 0.15 to 0.35, p < 0.001), and rotation showed a mean difference of 1.95° (SD 5.28, 90% CI: 0.64 to 3.26, p = 0.016) (Table 3). All other movement parameters were not statistically significant. None of the movements achieved clinical equivalence (Table 3).

Table 3

Predictability — Conventional Attachment Group n = 46 teeth · One-sample t-test (H_0: mean difference = 0) · TOST equivalence testing

Movement	Unit	Predicted Mean	Predicted SD	Achieved Mean	Achieved SD	Difference Mean	Difference SD	90% CI Lower	90% CI Upper	p-value (t-test)	TOST p-value	Conc
Mesiodistal	mm	-0.146	0.369	-0.087	0.195	-0.059	0.299	-0.133	0.014	0.184	1.000	Not s Not Equiv
Buccolingual	mm	0.114	0.533	0.067	0.423	0.047	0.348	-0.039	0.133	0.362	1.000	Not s Not Equiv
Occlusogingival	mm	0.400	0.483	0.154	0.262	**0.246**	0.402	0.146	0.346	**0.000***	1.000	Stat. Not Equiv
Tip	Degree(°)	-0.378	3.990	-0.609	2.189	0.231	3.873	-0.728	1.190	0.688	0.896	Not s Not Equiv
Torque	Degree(°)	0.856	4.325	0.013	2.783	0.842	3.694	-0.072	1.757	0.129	0.991	Not s Not Equiv
Rotation	Degree(°)	2.775	6.113	0.822	1.952	**1.953**	5.283	0.644	3.261	**0.016***	0.999	Stat. Not Equiv

** p < 0.05 (statistically significant). ! Shapiro–Wilk p < 0.05 (non-normal distribution; parametric tests applied under central limit theorem, n ≥ 45). Equivalence ma ±0.25 mm (linear movements); ±0.5° (angular movements). TOST p < 0.05 = clinically equivalent. Difference = Predicted − Achieved. Positive difference = overestimation by software.*

In the optimised attachment group (n = 44 teeth), buccolingual movement showed a mean difference of − 0.22 mm (SD 0.55, 90% CI: −0.36 to − 0.08, p = 0.011), and occlusogingival movement showed a mean difference of − 0.17 mm (SD 0.47, 90% CI: −0.29 to − 0.05, p = 0.018) (Table 4). No other movements were statistically significant, and none met the criteria for clinical equivalence (Table 4). Across both groups, variability remained substantial, particularly for angular movements (Tables 3 and 4).

Table 4
Predictability — Optimised Attachment Group. n = 45 teeth · One-sample t-test (H_0: mean difference = 0) · TOST equivalence testing

Movement	Unit	Predicted Mean	Predicted SD	Achieved Mean	Achieved SD	Difference Mean	Difference SD	90% CI Lower	90% CI Upper	p-value (t-test)	TOST p-value	Conc
Mesiodistal	mm	-0.093	0.450	0.005	0.362	-0.099	0.452	-0.212	0.014	0.149	1.000	Not s Not Equi
Buccolingual	mm	0.003	0.442	0.221	0.585	**-0.218**	0.552	-0.356	-0.079	**0.011***	1.000	Stat. Not Equi
Occlusogingival	mm	0.104	0.422	0.274	0.289	**-0.170**	0.467	-0.287	-0.053	**0.018***	1.000	Stat. Not Equi
Tip	Degree (°)	0.240	4.490	0.852	3.859	-0.612	4.920	-1.844	0.620	0.408	0.932	Not s Not Equi
Torque	Degree(°)	-0.315	3.943	-1.622	3.551	1.306	4.426	0.197	2.414	0.054	0.996	Not s Not Equi
Rotation	Degree(°)	1.287	7.590	1.243	3.315	0.044	7.040	-1.719	1.807	0.967	0.697	Not s Not Equi

** p < 0.05 (statistically significant). ! Shapiro–Wilk p < 0.05 (non-normal distribution; parametric tests applied under central limit theorem, n ≥ 45). Equivalence ma ±0.25 mm (linear movements); ±0.5° (angular movements). TOST p < 0.05 = clinically equivalent. Difference = Predicted − Achieved. Positive difference = overesti software.*

Between-group comparisons (LME analysis)

Between-group comparisons using linear mixed-effects models showed statistically significant differences in buccolingual and occlusogingival movements. Buccolingual movement showed a group effect of − 0.21 mm (90% CI: −0.38 to − 0.04, p = 0.040), and occlusogingival movement showed a group effect of − 0.42 mm (90% CI: −0.57 to − 0.27, p < 0.001) (Table 5). Mesiodistal movement was the only parameter to demonstrate between-group clinical equivalence (TOST p = 0.004) (Table 5). No other movements demonstrated equivalence.

Table 5
Optimised vs Conventional — Linear Mixed Effects Model Comparison n = 90 teeth (44 Opt, 46 Conv) · LME: Difference ~ Group + (1|Patient) · TOST equiv

Movement	Unit	Optimised Diff Mean	Optimised Diff SD	Conventional Diff Mean	Conventional Diff SD	Group Effect (Opt − Conv)	LME SE	90% CI Lower	90% CI Upper	p-value (LME)	TOST p-value	ICC
Mesiodistal	mm	-0.099	0.452	-0.059	0.299	-0.024	0.083	-0.161	0.1125	0.770	0.004	0.1
Buccolingual	mm	-0.218	0.552	0.047	0.348	-0.209	0.102	-0.378	-0.0415	0.040*	0.348	0.2
Occlusogingival	mm	-0.170	0.467	0.2464	0.402	-0.416	0.092	-0.568	-0.2651	< 0.001*	0.963	0
Tip	Degree(°)	-0.612	4.920	0.231	3.873	-0.600	0.967	-2.191	0.9907	0.535	0.541	0.1
Torque	Degree(°)	1.306	4.426	0.842	3.694	0.463	0.868	-0.964	1.8915	0.593	0.483	0
Rotation	Degree(°)	0.044	7.040	1.953	5.283	-1.802	1.327	-3.985	0.3806	0.174	0.835	0.0

** p < 0.05 (statistically significant). Yellow = significant difference. Green = clinically equivalent (TOST p < 0.05). Equivalence margins: ±0.25 mm (linear); ±0.5° (ar Effect = Optimised − Conventional from LME fixed effect. ICC = Intraclass Correlation Coefficient (proportion of variance due to patient-level clustering). LME: Dif + (1|Patient).*

Clustering and variability

The intraclass correlation coefficient (ICC) ranged from 0 to 0.28 across movement parameters (Table 5), indicating variable clustering at the patient level. Buccolingual movement showed the highest clustering (ICC = 0.28), followed by tip (ICC = 0.20) and mesiodistal movement (ICC = 0.13) (Table 5). These findings indicate that variability in outcomes was partly attributable to between-patient differences.

Measurement reliability

The intra-examiner reliability assessment demonstrated high reproducibility, with ICC values ranging from 0.80 to 0.95 across all movement parameters. The measurement error remained below the predefined equivalence thresholds (± 0.25 mm for linear and ± 0.5° for angular movements) further supporting the precision of the measurement protocol.

Other analyses

Exploratory confounder-adjusted analyses were conducted after adjustment for age, sex, and magnitude of planned movement (Table 6). Significant between-group differences remained for buccolingual, occlusogingival and rotational movements. No adjusted differences were observed for mesiodistal, tip or torque.

Table 6
Confounder-adjusted between-group comparisons for prediction error across the six movement outcomes

Outcome	Adjusted group effect (Optimised – Conventional)	SE	95% CI	p-value
Mesiodistal	-0.023	0.074	-0.169 to 0.122	0.752
Buccolingual	-0.273	0.112	-0.493 to -0.053	0.015
Occlusogingival	-0.322	0.109	-0.535 to -0.108	0.003
Tip	-0.774	0.903	-2.545 to 0.997	0.392
Torque	0.436	0.835	-1.201 to 2.073	0.602
Rotation	-2.548	0.962	-4.434 to -0.662	0.008

Adjusted for age, sex and magnitude of planned movement. Group effect is expressed as Optimised – Conventional for prediction error (predicted – achieved).

Dose–response analyses were then conducted to assess whether the magnitude of planned movement influenced prediction error. When signed prediction error was used as a measure of directional accuracy, significant associations were observed for mesiodistal, occlusogingival and rotational movements (Table 7). When absolute prediction error was used as a measure of discrepancy magnitude, increasing planned movement was associated with greater error across all six movement outcomes, with the strongest associations observed for rotation, occlusogingival movement and mesiodistal movement (Table 8).

Table 7
Association between magnitude of planned movement and signed prediction error (directional accuracy) across the six movement outcomes

Outcome	β coefficients for planned movement magnitude	SE	95% CI	p-value	R^2
Mesiodistal	-0.594	0.189	-0.965 to -0.223	0.002	0.212
Buccolingual	0.008	0.159	-0.303 to 0.320	0.958	0.095
Occlusogingival	0.450	0.221	0.016 to 0.884	0.042	0.298
Tip	0.112	0.284	-0.445 to 0.669	0.694	0.015
Torque	-0.117	0.211	-0.531 to 0.296	0.578	0.028
Rotation	0.803	0.107	0.593 to 1.014	< 0.001	0.391

Dependent variable: signed prediction error (predicted – achieved). Models were adjusted for age, sex and attachment group. Positive beta coefficients indicate increasing positive error with larger planned movement; negative coefficients indicate increasingly negative error with larger planned movement.

Table 8
Association between magnitude of planned movement and absolute prediction error across the six movement outcomes

Outcome	β coefficients for planned movement magnitude	SE	95% CI	p-value	R^2
Mesiodistal	0.601	0.155	0.296 to 0.905	< 0.001	0.334
Buccolingual	0.248	0.104	0.044 to 0.452	0.017	0.092
Occlusogingival	0.654	0.118	0.422 to 0.886	< 0.001	0.398
Tip	0.460	0.107	0.249 to 0.670	< 0.001	0.327
Torque	0.360	0.099	0.165 to 0.555	< 0.001	0.136
Rotation	0.738	0.072	0.596 to 0.879	< 0.001	0.676

Dependent variable: absolute prediction error. Models were adjusted for age, sex and attachment group. Positive β coefficients indicate greater discrepancy with increasing planned movement magnitude.

Exploratory subgroup analyses by sex and age (≤ 34 years vs > 34 years) showed that between-group differences were more pronounced for occlusogingival and rotational movements in females and in patients aged > 34 years (Table 9). These subgroup findings should be interpreted cautiously.

Table 9
Exploratory subgroup analyses of between-group differences in selected movement outcomes

Subgroup	Outcome	Adjusted group effect (Optimised – Conventional)	95% CI	p-value
Female	Buccolingual	-0.354	-0.653 to -0.055	0.020
Female	Occlusogingival	-0.464	-0.734 to -0.193	< 0.001
Female	Rotation	-3.344	-5.854 to -0.834	0.009
Male	Buccolingual	-0.111	-0.412 to 0.190	0.470
Male	Occlusogingival	-0.013	-0.262 to 0.235	0.917
Male	Rotation	-0.797	-2.989 to 1.395	0.476
Age ≤ 34 years	Buccolingual	-0.283	-0.581 to 0.015	0.063
Age ≤ 34 years	Occlusogingival	-0.126	-0.336 to 0.084	0.239
Age ≤ 34 years	Rotation	-1.889	-4.348 to 0.570	0.132
Age > 34 years	Buccolingual	-0.251	-0.570 to 0.069	0.124
Age > 34 years	Occlusogingival	-0.524	-0.881 to -0.167	0.004
Age > 34 years	Rotation	-3.764	-7.047 to -0.480	0.025
Subgroup analyses were exploratory. Age groups were defined using the sample median age of 34 years.				

Discussion

Our present study is the first to evaluate six distinct linear and angular movements exclusively on maxillary lateral incisors, incorporating clinical equivalence testing and assessing the influence of attachment design on outcome accuracy. This retrospective cohort study found that maxillary lateral incisor movements with clear aligners were more predictable for linear than for angular displacements. Previous studies have reported unintended movements such as lingual crown tipping and extrusion during retraction in extraction cases[13] and mesial movement with labial proclination during distalisation [14]. To minimise confounding variables, the present study focused exclusively on non-extraction cases with moderate treatment complexity, thereby enhancing internal validity and allowing a clearer assessment of the influence of attachment design on movement predictability. Although attachment design is an important biomechanical adjunct, tooth movement predictability is influenced by multiple factors, including space availability, aligner fit, material properties, and force decay [15]. Koletsi et al reported no significant improvement in predictability with the use of attachments or interproximal reduction [16]. Castroflorio et al observed that optimised attachments were more frequently prescribed for incisor movements, yet did not consistently enhance predictability [17]. Furthermore, bulky attachments may compromise esthetics and patient compliance. Given the limited evidence comparing attachment designs across multiple movement types, this study evaluated the accuracy of maxillary lateral incisors across six movements and the influence of conventional and optimised attachments.

Linear movements:

Consistent with the existing literature, linear movements were more accurate than angular movements in the present study [12].

Mesiodistal movement:

Mesiodistal movement showed no statistically significant difference between predicted and achieved values. In addition, it was the only movement to demonstrate clinical equivalence between attachment designs. The mean difference was small and variability was relatively low compared with other movements. From a practical perspective, this indicates greater consistent agreement between predicted and achieved outcomes. Across attachment types, no statistically significant differences were observed. The performance was comparable within clinically acceptable limits. However, this reflects agreement within thresholds rather than exact correspondence. It should not be attributed to any specific treatment factor.

This relatively favourable performance could be attributed to mesiodistal translation involving bodily movement along the arch, with the aligner maintaining broad surface contact on both the labial and lingual aspects of the tooth. The lateral incisor, despite its narrow form, responded reasonably well, which could be attributed to the force direction aligning with the aligner's primary mode of engagement. This is also partially consistent with the findings of Haouili et al., who reported modest accuracy for lateral incisors[6], and Castroflorio et al., who observed a loss of approximately 0.3 mm per 1 mm of prescribed mesiodistal movement, necessitating over-correction [17].

Buccolingual

Buccolingual movement showed no statistically significant overall difference between predicted and achieved values. However, clinical equivalence was not demonstrated. The mean difference was small, but the standard deviation indicated variability in individual outcomes. Between attachment designs, a statistically significant difference was observed, with greater underprediction in the optimised attachment. This difference persisted after adjustment for age,

sex and magnitude of planned movement. This may be because algorithmically placed optimised attachments may generate a different vector of force on the labial surface, inadvertently allowing more labiolingual drift than anticipated. Conventional attachments, placed at the clinician's discretion, may better stabilise the tooth in this plane because clinicians can orient them based on clinical judgement of the tooth's tendency to drift. However, previous studies have reported higher predictability for labiolingual movements of lateral incisors [6, 18].

However, clinical equivalence was not achieved, indicating that the discrepancy exceeded acceptable limits. From a practical perspective, although the magnitude of the difference was small, variability and patient-level clustering suggest heterogeneous outcomes. Therefore, while a difference between attachments was detected, neither attachment can be considered clinically superior.

Occlusogingival movement:

Occluso-gingival movement showed a statistically significant difference between predicted and achieved values in both attachment groups. The optimised attachment group exhibited greater underprediction than the conventional group. However, neither group achieved clinical equivalence, indicating limited intrinsic predictability of vertical movement regardless of attachment design. The mean difference was small, but the standard deviation indicated variability in individual outcomes. From a practical perspective, this indicates that predicting vertical movement remains less reliable. This behaviour may be attributed to the inherent biomechanical challenges of vertical tooth movement with clear aligners. Occluso-gingival movement depends on effective aligner seating and sustained force application, both of which are susceptible to minor discrepancies in aligner fit, occlusal interference, and material deformation. These findings are consistent with prior reports highlighting the need for over-correction and adjunctive mechanics for extrusion [19–22].

Angular movements:

Irrespective of the attachment design, angular movements were consistently less predictable than linear ones [23].

Tip

Tip demonstrated no significant differences between predicted and achieved values in both attachment groups, but showed wide variability in achieved outcomes, corroborating findings by D'Anto et al., who reported lateral incisor tip as one of the least predictable movements with high angular error [24]. These results indicate that tipping movements of lateral incisors remain unreliable with clear aligners. Biomechanically, tipping requires a moment to be applied to the crown, which in turn depends on the aligner's ability to generate a couple. The lateral incisor's short, tapered crown provides limited surface area for this, and the aligner tends to lose engagement as the tooth begins to tip, reducing further force delivery. If controlled tipping is needed, use sequential staging with small increments per aligner, and consider placing an additional manually designed attachment to enhance the moment arm.

Torque

Torque demonstrated the greatest variability among angular movements. These findings align with biomechanical explanations of insufficient force-couple generation and aligner disengagement during torque expression [25–27]. Dai et al. reported that only 42% of root torque could be achieved with clear aligners [28]. Another study by Ya-Ya Hong evaluated the efficacy of clear aligners for upper-incisor torque control using CBCT and found that the mean accuracy of upper-incisor torque control with clear aligners was 46.81%. They also concluded that root movement was more difficult than crown movement [29]. By contrast, Tepedino et al. concluded that clear aligners allowed predictable torque movements in non-extraction cases. The studied clear aligner system produced clinical outcomes comparable to the digital setup planning for torque movements of the anterior teeth [30]. However, they used digital models for evaluation, which do not include root movements, unlike CBCT.

Based on the above literature and our findings, torque of lateral incisors should be substantially overcorrected in the digital planning. Despite proposed solutions such as horizontal attachments or power ridges [31, 32], torque control of lateral incisors remains inherently limited. The exclusion of power ridges in this study highlights the limited capacity of attachment modifications alone to improve torque predictability.

Rotation:

Rotation showed a small mean difference between predicted and achieved values. However, the standard deviation was large, indicating substantial variability in individual outcomes. No statistically significant difference was observed, and clinical equivalence was not demonstrated. This indicates that, despite a low average discrepancy, outcomes were highly inconsistent. From a practical perspective, rotation cannot be considered clinically reliable, as the low mean error was not accompanied by consistent performance. There was no difference between the attachment designs, indicating that attachment design did not influence this variability. This finding highlights that movements with minimal mean error but high variability may still be clinically unpredictable. These findings are consistent with Castroflorio et al. and Fiorillo et al., who reported no significant improvement in rotational predictability with optimised attachments [17, 33]. While some studies have reported higher rotational accuracy [34, 35] variability remains high, particularly for lateral incisors due to limited crown surface area and reduced aligner grip. This may be attributed to the lateral incisor's round cross-section and lack of prominent undercuts, which make it the most difficult anterior tooth to derotate. It is wise to avoid planning large rotational corrections as single-phase movements.

Limitations

This study has several limitations. Best-fit crown superimposition for movement assessment does not directly capture root position. Therefore, angular movements, particularly torque, reflect crown-based estimates rather than true root movement. The absence of CBCT-based assessment limits the evaluation of root-level changes and should be considered when interpreting angular outcomes. Additionally, the accuracy of maxillary lateral incisor movement is constrained by the biomechanical limitations of clear aligners, including material deformation, force decay, and aligner-tooth disengagement [24–27, 34, 36, 37].

Generalisability

The retrospective design and inclusion of cases treated at a single centre by an experienced provider may limit generalisability to other clinical settings. Additionally, only non-extraction Invisalign Lite cases with relatively small planned movements were included which may not reflect more complex malocclusions or treatment protocols. The standardised treatment conditions may represent optimised clinical scenarios and may not fully capture the variability encountered in routine practice. Furthermore, differences observed between attachment groups may, in part, reflect variations in planned tooth movement rather than the isolated effect of attachment design. The findings should therefore be interpreted within the context of the treatment planning framework [38].

Conclusions

● Maxillary lateral incisor movements with clear aligners showed variable agreement between predicted and achieved outcomes, with greater variability in angular movements (tip, torque and rotation) than in linear movements.

● Mesiodistal movement was the only parameter that achieved clinical equivalence between attachment groups, indicating that differences between conventional and optimised attachments for this movement were within predefined clinically acceptable limits.

● Torque showed a statistically significant discrepancy between predicted and achieved values, indicating reduced expression of planned torque. Within-group analyses revealed discrepancies in occlusogingival and rotational movements in the conventional group and in buccolingual and occlusogingival movements in the optimised group.

● No consistent overall advantage of one attachment design over the other was observed across all movement types. Attachment design alone did not explain the variability in treatment outcomes.

● Confounder-adjusted analyses confirmed the robustness of these findings, with persistent differences in buccolingual, occlusogingival and rotational movements.

● Increasing the magnitude of planned movement was associated with a greater discrepancy between predicted and achieved outcomes, indicating reduced accuracy with larger prescribed movements.

● These findings indicate that discrepancies should be anticipated, particularly for angular movements and larger planned movements, and should be taken into account during treatment planning.

Declarations

Support & Funding

This study was self-funded.

Availability of data, code and other materials

It is available with the corresponding author upon request
Human Ethical approval and consent to participate and publish:

This study was approved by the research Ethics Committee - (SRB/SDC/PhD/ORTHO-2119/22/010). Written and informed consent was obtained from all the participants before the start of treatment for participation in the study and for publication of this research and accompanying images.

Competing Interests

W.S. is a key opinion leader and a speaker for Invisalign (Align Technology Inc., Santa Clara, CA).

Author Contribution

SM: Conceptualisation, Methodology, Investigation, Formal analysis, Data curation, Writing original draft, Writing - review and editing.A K Subramanian: Writing - review and editing. SA: Methodology, Formal analysis. NV: Conceptualisation, Methodology, Supervision, Writing - review and editing. WS: Data curation, Formal analysis, methodology. A Shetty: Methodology, Formal analysis, Writing - review and editing.

Data Availability

It is available with the corresponding author upon request

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Figures



Figure 1

Example of 3D superimposition between predicted and achieved models using Compare software (best-fit crown registration). Green areas indicate regions of deviation between planned and final tooth positions.

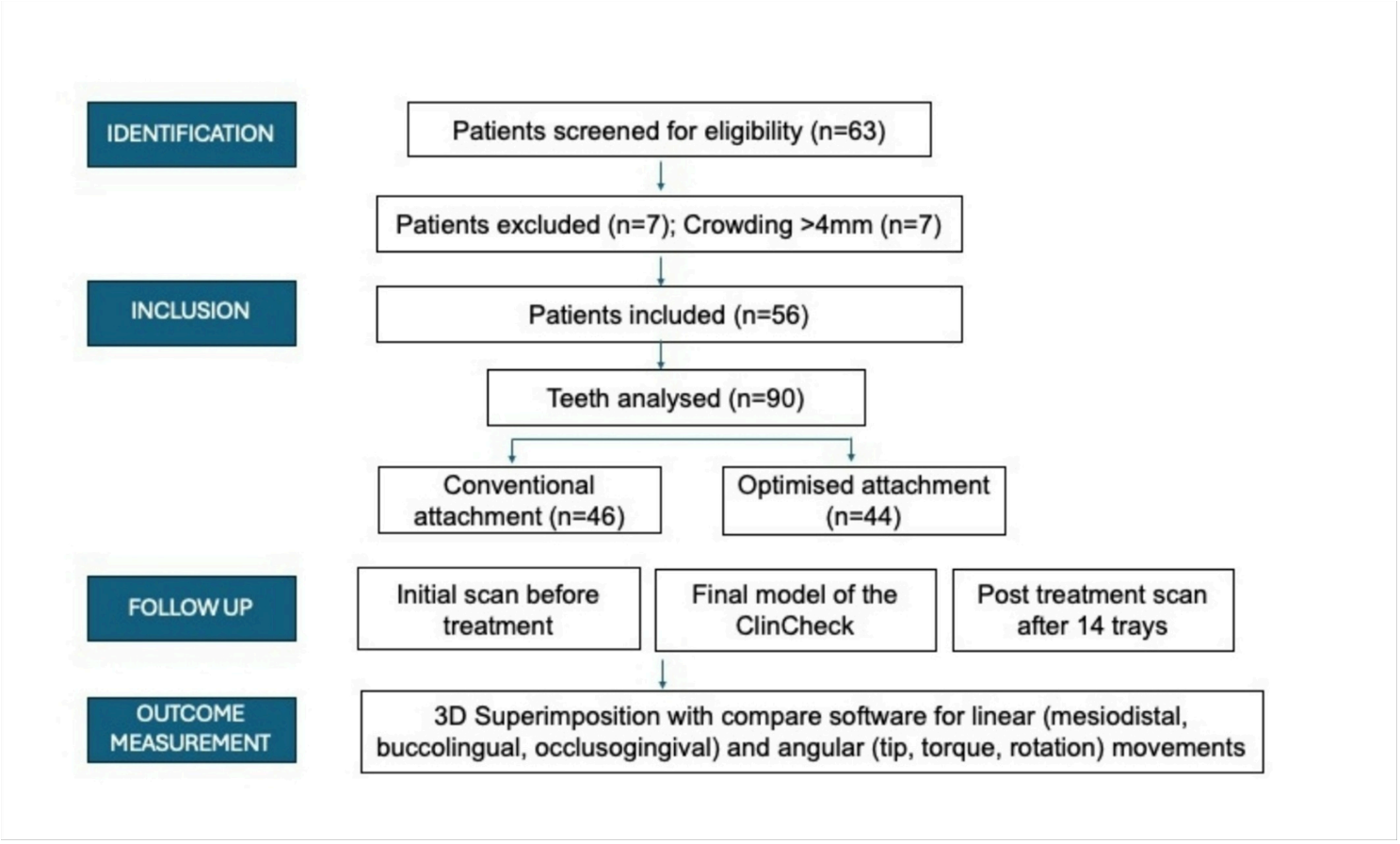


Figure 2

Participant Flow diagram

Supplementary Files

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- Samplesizelateralpdf.pdf