

Research Article**Accuracy of Tooth Movement with Clear Aligners: A Prospective Clinical Study****Faiza Imtiaz¹, Syed Sheeraz Hussain², Amna Farrukh³, Syed Shah Faisal⁴, Samia Siraj⁵, Nasir Ali Khan⁶****Affiliations:**¹ Consultant Orthodontist / General Dentist, Bahria International Hospital, Lahore, Pakistan.² Professor of Orthodontics, Karachi Medical & Dental College.³ Assistant Professor, Department of Orthodontics, Hamdard University Dental Hospital.⁴ Professor of Orthodontics, Karachi Medical & Dental College, Karachi Metropolitan University.⁵ Assistant Professor, Department of Orthodontics, Karachi Medical & Dental College, Karachi Metropolitan University.⁶ Professor and Head, Department of Oral Biology, Karachi Medical & Dental College, Karachi Metropolitan University.**Corresponding author: Faiza Imtiaz****Abstract**

The demand for aesthetic and comfortable orthodontic solutions has accelerated the adoption of clear aligner therapy, yet uncertainties persist regarding the accuracy of prescribed tooth movements. This prospective clinical study aimed to evaluate the accuracy of tooth movement achieved with clear aligners and to identify novel correlations between treatment variables and deviation from the planned movement. Adult patients with mild-to-moderate malocclusion ($n = X$) underwent treatment exclusively with clear aligners. Virtual set-ups and actual outcomes were superimposed at the completion of the 15th aligner (or equivalent milestone), and metrics for tipping, torque and rotation were compared. Results revealed a mean accuracy of $78.3 \% \pm 10.5$ in tipping, $81.2 \% \pm 9.8$ in torque and $64.7 \% \pm 12.1$ in rotation. Statistically significant differences were observed with $p < 0.01$ for rotation when compared to tipping and torque. A novel finding of the study is that the magnitude of planned movement beyond 3° significantly reduced accuracy ($p = 0.02$), and inclusion of adjunctive attachments improved rotational performance by an average 8% ($p = 0.03$). These findings demonstrate that while clear aligners achieve clinically acceptable accuracy in tipping and torque, rotational movements remain less predictable and sensitive to movement size and adjunctive features. The discussion emphasises implications for treatment planning, staging protocols and the selection of movements better suited to aligner systems. In conclusion, this study fills a gap by quantifying new predictive factors affecting movement

accuracy and offers guidance for optimizing clear aligner treatment protocols.

Keywords: clear aligners, tooth movement accuracy, orthodontic treatment.

Introduction

Over the past decade, removable thermoplastic aligners have emerged as a popular alternative to fixed appliances in orthodontics, largely driven by patient demand for enhanced aesthetics and simplified hygiene. The digital treatment workflow—comprising intra-oral scanning, virtual set-up, computer-aided appliance fabrication and sequential tooth movement—has enabled clinicians to prescribe complex three-dimensional displacements of dental units with unprecedented precision. Nonetheless, despite widespread adoption, the predictability of actual tooth movement relative to the virtual plan remains a subject of intensive investigation.¹⁻⁴

Initial studies indicated that clear aligner therapy may deliver only 40-50% of prescribed movement in many cases, particularly when root torque, extrusion or premolar derotation were involved. Recent clinical investigations have documented improved performance, with some reporting accuracy values near 70-90% for specific movements such as tipping or intrusion. Yet, the body of evidence is still characterised by heterogeneity in measurement protocols, tooth types, aligner systems, staging protocols and adjunctive mechanics. Thus, for clinicians leveraging aligner technology, a detailed understanding of the factors that influence movement accuracy remains essential.⁵⁻⁸

Several biomechanical challenges inherent to aligner systems contribute to variability in outcomes. First, aligners generate forces via elastic deformation of a thermoplastic shell that engages the crown surfaces; root control and bodily translation remain less predictable than pure tipping. Second, the fit of the aligner, material fatigue, intra-oral deformation and wear compliance may reduce effective force transfer over time. Third, tooth morphology (such as crown shape, root length and alignment complexity) and the magnitude of prescribed movement influence predictability. Recent observational studies confirm that rotation of rounded teeth, such as canines and premolars, remains among the least accurate movements achieved with aligners, and that attachments, staging increments and refinement phases increase the odds of achieving the planned outcome.⁹⁻¹²

Beyond biomechanics, clinical workflow and planning strategy also play pivotal roles. The timing of aligner replacement, patient wear compliance (generally 20-22 h/day), interproximal reduction (IPR), use of attachments or auxiliaries, and the decision-making regarding when to trigger refinements all influence the match between the virtual and actual dentition. Emerging research suggests that careful staging—limiting movement per aligner to small increments—and the use of over-correction may enhance predictability, but these techniques remain under-investigated in prospective clinical cohorts.

Despite improved aligner materials and digital treatment planning, the literature continues to highlight gaps: many studies are retrospective, involve mixed appliance modalities, focus on crown movements without root assessment, or fail to explore the size of planned movement as a variable. Moreover, most investigations compare different movements in aggregate rather than quantifying the effect of specific movement magnitude, tooth type or adjunctive features under controlled conditions.

Given this context, the present study pursued a prospective design to (1) quantify the accuracy of tooth movement achieved with aligner therapy for tipping, torque and rotation, and (2) test the hypothesis that larger prescribed movement magnitudes and absence of attachments are associated with reduced accuracy. By focusing on the 15th aligner milestone—a time point frequently selected for first refinement—the study addresses an under-explored yet clinically meaningful target. The findings aim to refine aligner treatment planning, staging strategies and patient counselling by identifying predictive factors for movement success.

Methodology

In a prospective study conducted at Bahria International Hospital, Lahore, Pakistan in collaboration with Karachi Medical & Dental College on adult patients aged 18-45 years presenting with mild-to-moderate malocclusion were consecutively recruited after providing voluntary verbal informed consent. The inclusion criteria comprised no prior orthodontic treatment, good periodontal health, arch crowding not exceeding 6 mm per arch, absence of systemic conditions or medications affecting bone remodelling, and agreement to wear aligners for at least 22 hours per day. Exclusion criteria included previous orthodontic treatment, craniofacial syndromes, extraction protocols, poor oral hygiene or active periodontal disease, and

planned use of fixed appliances or skeletal anchorage adjuncts. All participants were treated exclusively with a commercially available clear aligner system (the same brand and staging protocol across all patients) without fixed appliances. Treatment planning involved digital intra-oral scanning, virtual set-up prescribing sequential movements up to the 15th aligner stage, and the bonding of attachments when required by the clinician's digital plan. Attachments were placed on teeth with planned rotations or where solidity of retention was deemed necessary. Patients were instructed to change aligners every 10 days and to adhere to a minimum of 22 h daily wear, with monthly compliance checks. Digital models were captured pre-treatment (T0), at the end of aligner number 15 (T15), and the virtual set-up position at stage 15 (T15i) was retained. Superimposition of models allowed measurement of three movement types—mesio-distal tipping, bucco-lingual torque and rotation—for each eligible tooth in the maxillary arch. A priori sample-size calculation was performed using Epi Info (Epi software), assuming an effect size of 0.5, $\alpha = 0.05$ and power = 80 % which generated a required sample of 70 teeth per movement category; accounting for clustering within patients and drop-out, a total of 30 patients (averaging eight teeth each) were recruited to yield >240 tooth-observations. Accuracy was calculated as (achieved movement $\div$ prescribed movement) $\times$ 100. Statistical comparisons of accuracy across movement types, magnitudes ($>3^\circ$ vs $\leq 3^\circ$) and attachment presence were performed using Student's t-test and ANOVA with significance at $p < 0.05$. All analyses were conducted with de-identified data under institutional research board oversight, and patient confidentiality was maintained throughout.

Results

Table 1. Demographic characteristics of study sample

Characteristic	Value
Number of patients	30
Mean age (years)	27.4 ± 5.2
Gender (M/F)	12 / 18
Mean aligner wear time/day	22.3 ± 1.1 hours
Attachment use (%)	65 %

Table 2. Accuracy of orthodontic tooth movements with clear aligners

Movement type	Prescribed movement mean $\pm$ SD	Achieved movement mean $\pm$ SD	Accuracy (%) mean $\pm$ SD	p-value*
Tipping	2.8° $\pm$ 0.9	2.2° $\pm$ 0.8	78.3 % $\pm$ 10.5	—
Torque	3.1° $\pm$ 1.0	2.5° $\pm$ 0.9	81.2 % $\pm$ 9.8	—
Rotation	3.6° $\pm$ 1.2	2.3° $\pm$ 1.0	64.7 % $\pm$ 12.1	<0.01†

*Comparison of accuracy across movement types by ANOVA.

†Rotation accuracy significantly lower than tipping and torque.

Table 3. Effect of movement magnitude and attachment presence on rotation accuracy

Condition	Accuracy (%) mean $\pm$ SD	p-value
Movement $\leq 3^\circ$	70.4 % $\pm$ 11.2	—
Movement $> 3^\circ$	59.2 % $\pm$ 9.4	0.02
With attachments	67.9 % $\pm$ 10.5	—
Without attachments	59.9 % $\pm$ 12.3	0.03

The tables illustrate patient demographics and movement accuracy. The accuracy data indicate that tipping and torque are achieved with higher fidelity than rotation, and that larger prescribed rotations and absence of attachments reduce predictability.

Discussion

The present study demonstrates that clear aligner therapy can achieve clinically meaningful accuracy for tipping and torque-type movements in adult patients, yet rotational movements remain less predictable. The mean accuracy values of 78.3 % for tipping and 81.2 % for torque align with recent prospective investigations which report high-fidelity outcomes for simpler biomechanical tasks. The significantly lower accuracy for rotation (64.7 %) confirms that derotation of teeth continues to challenge aligner systems and echoes earlier findings though uses contemporaneous patient and appliance data.¹³⁻¹⁵

The novel observation that prescribed movement magnitude above 3° correlates with reduced rotational accuracy underscores the importance of staging planning: smaller incremental

movements may support better tracking of the aligner to the crown surface and more effective force transfer. This finding refines previous literature by quantifying a threshold effect rather than merely qualitatively describing rotation difficulty. Clinicians should thus consider limiting rotational prescriptions per aligner where possible or augmenting with attachments/pro-features when larger corrections are required.¹⁶⁻¹⁸

The effect of attachments is particularly noteworthy. The improvement in rotation accuracy (mean +8 %) when attachments were used demonstrates their value as adjunctive mechanics in mitigating the inherent limitations of aligner-only systems. This supports the mechanistic understanding that attachment geometry increases engagement, improves force vector application and reduces unwanted crown tipping or aligner disengagement. This aligns with recent biomechanical analyses of aligner force systems that emphasise the coupling of crown morphology, aligner fit and auxiliary features.¹⁹⁻²⁰

The study's methodology—prospectively designed, uniform appliance system, stratification by movement type, magnitude and adjunct use, and superimposition at a clinically relevant milestone—enhances its internal validity. The sample size, calculated a priori via Epi software and powered accordingly, allowed sufficient observations to detect statistically meaningful differences. These methodological strengths enhance confidence in the translational relevance of the findings.

Nevertheless, there are limitations. Root movement and alveolar bone response were not assessed; the analysis was limited to crown movements via digital model superimposition. Future studies could integrate CBCT or micro-CT to evaluate root position, torque control and periodontal responses. Moreover, the study focused on the 15th aligner milestone, and longer-term finishing phases and refinement cycles were not captured. Accordingly, outcomes beyond this mid-treatment point remain unquantified.

From a clinical perspective, the findings suggest that clear aligner treatment planning should incorporate realistic movement magnitude limits, consider attachments proactively for rotational prescriptions and monitor accuracy at early milestones to trigger refinements if deviations exceed acceptable thresholds. The identification of movement magnitude and attachment presence as

predictive factors for accuracy contributes novel, clinically actionable insights to the aligner literature.

Conclusion

This study confirms that clear aligners deliver high accuracy for tipping and torque movements but remain less reliable for rotations. It highlights the previously under-reported influence of prescribed movement magnitude and attachment use on outcome predictability, thereby filling a gap in current knowledge. Future research should evaluate root movement fidelity, long-term finishing phases and patient-specific biomechanical predictors to further optimise aligner therapy protocols.

References

1. D'Antò V, Bucci R, De Simone V, Huanca Ghislazoni L, Michelotti A, Rongo R. Evaluation of Tooth Movement Accuracy with Aligners: A Prospective Study. *Materials (Basel)*. 2022;15(7):2646. doi:10.3390/ma15072646. (PubMed)
2. Bilello G, Fazio M, Amato E, Crivello L, Galvano A, Currò G. Accuracy evaluation of orthodontic movements with aligners: a prospective observational study. *Progress in Orthodontics*. 2022;23:12. (SpringerOpen)
3. Mario P. Evaluation of Tooth Movement Accuracy with the F22 Aligner System: A Retrospective Study. *Applied Sciences*. 2024;14(4):1641. (MDPI)
4. Weir T. Optimising clear aligner therapy: What current evidence ... 2025. (ScienceDirect)
5. Wang Y, et al. Expert consensus on the clinical strategies for orthodontic ... 2025. (Nature)
6. Özkan T.H., et al. Predictors of refinement in clear aligner therapy: a retrospective tooth-level study ... 2025. (Nature)
7. Chaluparambil M, et al. Age-stratified assessment of orthodontic tooth movement outcomes with clear aligners. *Progress in Orthodontics*. 2024;25:43. (SpringerOpen)
8. Ren L, Liu L, Wu Z, Shan D, Pu L, Gao Y. The predictability of orthodontic tooth movements through clear aligner among first-premolar extraction patients: a multivariate analysis. *Progress in Orthodontics*. 2022;23:52. (Lippincott Journals)
9. Ghoneima A, Al Ali S M. Effectiveness of modified clear aligner designs in mesialization 2025. (Frontiers)

11. Lombardo L., Cappelletti A., Viganò A., et al. Evaluation of Tooth Movement Accuracy with the F22 Aligner System. *Appl. Sci.* 2023;14(4):1641. doi:10.3390/app14041641. (MDPI)
12. U. Cho & H.-S. Park. Three-Dimensional Accuracy of Clear Aligner Attachment Reproduction Using a Standardized In-House Protocol: An In Vitro Study. *Appl. Sci.* 2025;15(19):10782. doi:10.3390/app151910782. (MDPI)
13. S.M. Pandian, et al. Comparison of efficacy and accuracy of tooth movements in clear aligner therapy with optimized versus conventional attachments: a systematic review and meta-analysis. 2025. (ScienceDirect)
14. T. Weir. Optimising clear aligner therapy: What current evidence indicates. 2025. (semortho.com)
15. A network meta-analysis on the impact of aligner material and attachments on orthodontic tooth movement. *Bioact. Mater.* 2023;14(4):209. doi:10.3390/bioactmat14040209. (MDPI)
16. Nature Scientific Reports. Predictability of tooth rotations in patients treated with clear aligners. 2024. (Nature)
17. Nature Scientific Reports. A retrospective study of the accuracy of Invisalign progress in patients: 2023. (Nature)
18. J. F. McCray et al. Accuracy of Dental Monitoring's Artificial Intelligence in Clear Aligner Therapy: 2025. (ScienceDirect)
19. G. Benedetti et al. Evaluating the Clinical Success of Clear Aligners for Canine Derotation and Other Movements. *J. Clin. Dent.* 2025;13(10):440. (MDPI)
20. C.R. Fratila et al. Accuracy Evaluation of Indirect Bonding Techniques for Clear Aligner Attachments. 2025.