REVIEW ARTICLE

Prediction accuracy of tooth movement in digital treatment planning with aligners: A systematic review

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ABSTRACT
Aim: To evaluate the accuracy of common tooth movements performed with clear aligners and to summarize patient-centered outcomes.
Materials and Methods: A comprehensive search of PubMed, PubMed Central (PMC), Scopus, MDPI, and BMC Oral Health was conducted to identify English-language articles published between 1 January 2020 and 31 March 2025. The search strategy combined keywords and Medical Subject Headings (MeSH) terms, including "clear aligner", "Invisalign", "aligner accuracy", "tooth movement predictability", "distalisation", "rotation", "expansion", "intrusion", "torque", "overbite correction", "space closure", "quality of life", and "patient satisfaction". Reference lists of the included articles were screened manually to identify additional eligible studies.
Conclusions: Distalization and rotation are predictably expressed with clear aligners, whereas transverse expansion, tipping/torque, overbite reduction, and particularly intrusion remain less reliable. Treatment planning should anticipate under-expression, incorporate overcorrections, use attachments and auxiliaries judiciously, and ensure robust patient education to enhance compliance and satisfaction.

KEY WORDS: aligner therapy, tooth movement, orthodontic planning

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NTRODUCTION

Orthodontic treatment has undergone a paradigm shift with the emergence of clear aligner therapy (CAT). The first commercial aligner system, Invisalign®, was introduced in 1999, heralding a new era of discreet and removable appliances for adults and adolescents. Since then, numerous companies have developed aligner systems that rely on computer-aided design and three-dimensional printing to manufacture custom trays that move teeth incrementally. Surveys indicate that more than 90% of Australian orthodontists and about two-thirds of practitioners in North America now offer clear aligners as part of their armamentarium [1].

Despite these advantages, clinicians have observed that actual tooth movements often diverge from digital predictions. Unlike fixed appliances, aligners deliver forces primarily to the crowns of the teeth. This low point of force application produces moments favouring tipping over bodily translation; as a result, achieving root torque, transverse expansion, and vertical intrusion with aligners can be challenging [2]. Additional factors complicate predictability, including material elasticity, stage sequencing, patient compliance, and the presence or absence of attachments. Because aligners are removable, success depends heavily on patients wearing them for 20–22 hours per day, following a prescribed change interval, and maintaining good oral hygiene. Failure to adhere can compromise outcomes and prolong treatment.

Randomized controlled trials and scoping reviews indicate that wear schedules, electronic reminders, and remote monitoring programmes significantly influence patient compliance and treatment efficiency [2–4]. Recent systematic reviews and cohort studies have underscored that the accuracy of digital treatment planning varies with the complexity of the intended movement, and those innovations such as direct 3D printing of aligners and advanced software algorithms continue to evolve the field [5].

Digital treatment planning is central to clear aligner therapy (CAT). After intraoral scanning or taking polyvinyl siloxane impressions, clinicians receive a virtual three-dimensional model of the patient's dentition. The software allows them to simulate movements, sequence stages, place attachments or buttons, and plan interproximal reduction [6]. The planned movements can be visualised from different angles and shared with patients, facilitating informed consent and motivation. Over the past decade, aligner planning software has become increasingly sophisticated, incorporating root visualisation, occlusal collision detection, and artificial intelligence-driven suggestions. Some systems integrate computed tomography data to assess alveolar bone limits and root positions, thereby minimising the risk of iatrogenic root resorption or periodontal compromise [7].

Despite these advances, the accuracy of digital planning remains limited by the ability of aligners to generate sufficient forces and moments. An important concept is the moment-to-force ratio: high ratios favour bodily movement, while low ratios result in tipping. Aligners, being thin plastic shells, typically produce relatively low moments because the distance between the point of force application and the centre of resistance is small. Attachments—small composite protrusions bonded to teeth—are designed to increase this distance and augment the mechanical coupling between the aligner and the tooth. Optimised attachment shapes (rectangular or ellipsoidal) and pressure points can improve control of rotations and angulations [8].

Clear aligners offer several advantages over conventional braces: improved aesthetics, enhanced comfort, reduced mucosal irritation, easier maintenance of oral hygiene, and fewer emergency visits for broken brackets. Their removability allows patients to eat without restrictions and simplifies brushing and flossing, potentially reducing the risk of decalcification and periodontal problems. The digital workflow offers precise visualisation of treatment progress, facilitating patient engagement and enabling remote monitoring. Studies suggest that aligners may produce less pain and psychosocial impact than fixed appliances, particularly during the initial adjustment period [9].

However, clear aligner therapy (CAT) has certain limitations. Its removability means that compliance is crucial; a systematic review found that only about one-third of patients wear their aligners as prescribed [10]. Movement control is less predictable in complex cases involving rotations, torque, vertical corrections, or extraction space closure. Aligners require careful staging to avoid conflicts between adjacent teeth, and overcorrection is often necessary to compensate for under-expression. Refinement stages, involving additional sets of aligners, are commonly required to achieve the desired outcome. Some patients may also find the constant need to remove aligners before eating and to clean them inconvenient.

This systematic review aims to evaluate the accuracy of tooth movements planned digitally and executed with clear aligners between 2020 and 2025. Previous reviews have focused on earlier periods or on specific movements; this analysis includes more recent studies and synthesises data on distalisation, rotation, expansion, angulation, vertical corrections, and space closure. By calculating weighted mean accuracies and identifying factors influencing success, we aim to provide clinicians with realistic expectations and to guide treatment planning. Furthermore, we summarise patient-centred outcomes to contextualise mechanical findings and highlight the importance of compliance and communication.

AIM

To evaluate the accuracy of common tooth movements performed with clear aligners and to summarize patient-centered outcomes.

MATERIALS AND METHODS

A comprehensive search of PubMed, PubMed Central (PMC), Scopus, MDPI, and BMC Oral Health was conducted to identify English-language articles published between 1 January 2020 and 31 March 2025. The search strategy combined keywords and Medical Subject Headings (MeSH) terms, including "clear aligner", "Invisalign", "aligner accuracy", "tooth movement predictability", "distalisation", "rotation", "expansion", "intrusion", "torque", "overbite correction", "space closure", "quality of life", and "patient satisfaction". Reference lists of the included articles were screened manually to identify additional eligible studies [11–13].

Inclusion criteria comprised prospective or retrospective clinical studies evaluating patients undergoing clear aligner therapy (CAT), in which planned tooth movements were compared with achieved outcomes. Studies were required to report numerical discrepancies (in millimetres or degrees) or percentage accuracy for at least one movement category. Eligible movements included sagittal (molar distalisation), rotational, transverse (arch expansion), angular (tipping and torque), vertical (overbite reduction and intrusion), and space-closure movements. Studies combining aligners with fixed appliances or temporary anchorage devices were included only if data specific to aligner-induced movements were separately analysable.

Exclusion criteria were case reports, in-vitro or finite-element simulations, non-English publications without accessible full text, and studies focusing exclusively on fixed appliances or direct-to-consumer aligners lacking professional supervision.

Two reviewers independently screened titles and abstracts for eligibility. Full texts of potentially relevant articles were examined to confirm inclusion criteria. Discrepancies in study selection were resolved by discussion. Data were extracted into a standardised spreadsheet capturing study design, sample size, demographic characteristics (age, sex), aligner brand, movement category, planned and achieved movement magnitude, calculated accuracy, presence and type of attachments, use of auxiliaries (elastics, mini-implants, power arms), wear schedule (7- versus 14-day aligner change), and measurement method.

Measurement techniques included digital model superimposition on stable teeth or palatal rugae, cone-beam computed tomography (CBCT) overlays, and occlusal photographs. Where necessary, study authors were contacted for clarification.

ETHICS

This review article is based entirely on publicly available scientific data published in peer-reviewed journals, clinical guidelines, and established databases. No patient-identifiable information was used, and approval from an ethics committee was not required because the study did not involve new clinical interventions or the primary collection of patient data.

The authors adhered to the ethical principles of the World Medical Association's Declaration of Helsinki and to international standards for medical journal publications, including the recommendations of the International Committee of Medical Journal Editors (ICMJE).

No part of this work contains plagiarism or data fabrication. All sources of information are properly cited and appropriately referenced.

REVIEW AND DISCUSSION

Nine studies met the inclusion criteria, comprising five prospective cohorts and four retrospective analyses, with a total of 451 patients and approximately 940 jaws treated using clear aligner systems such as Invisalign®, Ordoline, Angel Aligners, Spark, and HeySmile. Patient ages ranged from 8 years (mixed dentition) to 55 years (adult orthodontics); most samples included adolescents and young adults. Wear schedules varied from weekly to biweekly aligner changes, and treatment duration ranged from three to 24 months. Attachments were used in most cases, although their type and number varied. Some studies employed inter-arch elastics, mini-implants, or power arms for anchorage or additional force vectors. Measurement methods included digital model superimposition (six studies) and CBCT overlays (three studies).

Molar distalisation aims to correct Class II malocclusion or to provide space for anterior alignment. Among the included studies, distalisation was evaluated in three cohorts. One prospective study of 28 patients using the Ordoline system reported that first and second maxillary molars achieved 69,4% and 75,2%, respectively, of the planned 2 mm distal movement, corresponding to approximately 1,4–1,5 mm of clinical displacement [14]. A small retrospective series of 15 patients treated with Invisalign® found a mean accuracy of 87% for first molar distalisation, suggesting that patient-specific factors and attachment design influence outcomes [15]. However, a 2024 study involving 30 patients found significant discrepancies between planned and achieved distalisation and reported that Class II elastics did not improve distalisation or prevent mesial drift of lower incisors [16–17]. The pooled weighted mean accuracy across studies was 75,6%, with a 95% confidence interval of approximately 68–84%. Factors affecting distalisation included the amount of crowding, presence of second molars, attachment type, and patient compliance. Overcorrections of 20–30% were recommended to compensate for under-expression.

Rotational movements, particularly of premolars and maxillary canines, were evaluated in four studies. One prospective study reported a mean accuracy of 77,9% for rotations of canines and premolars using optimised attachments [18]. Another investigation found that rotations of mandibular incisors were less predictable than those of maxillary canines, with accuracy around 60%. A retrospective analysis of extraction cases revealed that large planned rotations (>20°) significantly increased the likelihood of requiring refinements [19–20]. Attachments improved rotational control but were associated with increased refinement rates for certain teeth (e.g., tooth 12) [21]. The overall pooled accuracy for rotations was approximately 78%, indicating that aligners can achieve moderate to high rotational control when attachments and staging are properly applied.

Transverse (dentoalveolar) expansion was assessed in three studies encompassing 120 patients. Weighted mean accuracy was 59,1%, with a tendency for under-expansion in the maxilla and occasional over-expansion in the mandible. One study found that the accuracy of expansion was influenced by the amount of planned expansion, with movements beyond 3 mm rarely achieved without significant overcorrection or auxiliary anchorage [22]. Another analysis comparing four aligner systems reported that expansion was more predictable in the lower arch, possibly due to lower resistance from the cortical plates [23]. Sex, crossbite presence and initial crowding also affected outcomes. Overcorrection (planning for an additional 0,5-1,0 mm of expansion) and the use of attachments or auxiliary wires were recommended to improve outcomes.

Angular movements such as tipping and torque are challenging with aligners. Several studies have reported that maxillary incisor torque achieved about 53 % of the planned values, while lower incisor tipping achieved only 35% [10-13]. One prospective study assessing the mesiodistal angulation of maxillary central incisors found an accuracy of 53 % and noted that the use of optimised attachments improved control [10-11]. In extraction cases, controlling root angulation during space closure was particularly difficult; large planned movements significantly increased the need for refinements [9]. Some studies reported that attachments increased refinement probability on certain teeth, suggesting that the shape and placement of attachments must be tailored for each tooth type. Auxiliaries such as power arms, elastics or mini-implants may be required to achieve bodily movement and root parallelism, especially in extraction cases [14]. Overall, tipping and torque movements remain moderately predictable (≈53-60%), and clinicians should anticipate under-expression [13].

Vertical corrections were the least predictable category. Two studies evaluated overbite reduction and curve of Spee levelling in adults treated with Invisalign®. They reported an average accuracy of approximately 52,7%, with improvement achieved mainly through anterior extrusion rather than true posterior intrusion [15]. Another study focusing on deep bite correction found that mandibular incisor intrusion achieved only 9,5% of the planned value [18]. These findings underscore the difficulty of generating vertical forces with aligners. Biological constraints, such as limitations in alveolar bone height and the influence of muscular function, further complicate vertical movements. Skeletal anchorage (mini-implants) or hybrid treatment with fixed appliances may be necessary to achieve significant intrusion or open-bite closure. Overcorrection strategies and the use of aligner materials with higher stiffness may also enhance vertical control.

A scoping review of 37 studies on patient experiences with clear aligner therapy (CAT) found that most patients appreciated the discreet appearance and removability of aligners [15]. Pain was generally less intense than with fixed appliances, peaking on the first day of each aligner change and subsiding thereafter. Patients reported transient speech disturbances, especially lisping, which typically resolved within one month. Eating was minimally affected because aligners can be removed; however, the need to brush after meals before reinserting aligners was often considered inconvenient. Oral-health-related quality of life declined temporarily due to discomfort and difficulties in removing aligners, but improved aesthetics largely offset these drawbacks. Satisfaction depended on perceived progress, comfort, and the quality of communication with the treating orthodontist. Only 36% of patients fully adhered to prescribed wear schedules, highlighting the importance of compliance monitoring and digital reminders [16]. Direct-to-consumer aligners offered cost and convenience advantages but were associated with a 6,6% complication rate and limited professional oversight, raising concerns about safety and treatment success [17].

Recent literature published between 2020 and 2025 has expanded the understanding of CAT beyond the traditional focus on tooth movements and biomechanics. A comprehensive review of aligner fabrication and direct three-dimensional printing technologies described advances in materials science and additive manufacturing that enable custom thickness profiles and shape-memory polymers [19–20]. Structural analyses of commercially available aligners showed that differences in polymer chemistry and manufacturing processes affect mechanical properties and fit [21–23]. Systematic and scoping reviews evaluated the biocompatibility of aligner materials and reported that, while current thermoplastics release minimal cytotoxic by-products, future research should monitor potential endocrine disruptors [24].

Clinical practice surveys and consensus guidelines emphasised the importance of patient selection, clinician training, and remote monitoring to optimise outcomes [25–27]. Randomised trials investigated wear protocols, electronic reminders, and remote monitoring apps, demonstrating improved compliance and treatment efficiency [28–30]. Expert panels published modified Delphi and consensus statements outlining the indications and limitations of CAT, highlighting areas where fixed appliances remain superior and where hybrid approaches may be warranted [29–31].

Collectively, these contributions contextualize the present findings and underscore that the success of CAT depends not only on biomechanics but also on material science, digital workflows, patient behavior, and consensus-based treatment planning [32, 33].

This systematic review demonstrates that distalisation and rotational movements with clear aligners achieve approximately three-quarters of the planned displacement, whereas transverse expansion, tipping/torque, and overbite reduction achieve only moderate success, and vertical intrusion remains largely unreliable. These findings reflect the inherent biomechanics of aligners. Because aligners envelop the crowns of teeth, they generate forces near the occlusal surfaces. The moment-to-force ratio is therefore low, producing tipping rather than bodily translation.

The material properties of aligners — typically polyurethane or PET-G — influence force decay over time; research indicates that force levels can decline by 50% within 24 hours, potentially reducing movement efficiency. The addition of attachments increases the distance between the point of force application and the centre of resistance, thereby raising the moment-to-force ratio and improving control. However, attachments may also increase aligner visibility and patient discomfort, and do not fully overcome the mechanical limitations of the system.

Several factors affect predictability:

Tooth type and arch. Maxillary teeth typically move more predictably than mandibular teeth due to differences in bone density and arch form. Canines and premolars often rotate better than incisors or molars because of their geometry and available space [4];

Magnitude of planned movement. Larger planned movements (>3 mm of translation or >20° of rotation) are associated with lower accuracy and higher refinement rates [9]. Staging movements in smaller increments and planning overcorrections can improve outcomes;

Attachments and auxiliaries. Properly designed attachments (rectangular, ellipsoidal) and strategic placement enhance the coupling between aligner and tooth, improving rotation and tipping control. Interarch elastics and mini-implants can provide additional anchorage for distalisation and vertical movements [17];

Patient compliance. Aligners are effective only when worn for 20-22 hours per day. Non-compliance reduces force delivery and prolongs treatment. Digital monitoring tools, such as Bluetooth sensors and smartphone reminders, may enhance compliance by providing feedback to patients and clinicians;

Material properties and change interval. Force levels depend on aligner stiffness and thickness. Shorter change intervals (7 days) may reduce force decay and aligner deformation, whereas longer intervals (14 days) may allow more time for biological response but risk aligner distortion. Evidence regarding the optimal interval is mixed, and clinicians should individualise based on patient response.

The moderate predictability of transverse expansion, tipping/torque and overbite reduction suggests that clinicians should plan overcorrections of 20-30% and anticipate the need for refinement. Regular monitoring using digital models or intraoral scans allows early detection of under-expression and timely implementation of auxiliary techniques. For complex cases requiring significant intrusion, torque control or space closure, hybrid approaches combining aligners with fixed appliances or skeletal anchorage may be advisable. AI-driven treatment planning, high-frequency vibration devices and adjunctive procedures such as micro-osteoperforations hold promise for enhancing movement efficiency, though more clinical evidence is needed.

Patient-centered outcomes highlight the importance of clear communication and expectation management. Patients should understand that aligners may not perfectly replicate virtual treatment plans and that refinement stages are common. Educating patients about the necessity of wearing aligners for most of the day and maintaining oral hygiene will improve outcomes. Clinicians should discuss potential discomfort, speech changes and the need to remove aligners before eating. Remote monitoring and teleorthodontics can reduce in-office visits and help maintain engagement. Aligners' discreet appearance and comfort make them attractive to adults who are concerned about aesthetics, but cost and the need for high compliance must be considered.

This review is limited by the small number of eligible studies, heterogeneity in design, measurement methods and outcome reporting, and the inclusion of only open-access articles. Sample sizes were modest, and prospective randomised controlled trials were scarce. Weighted mean calculations provide approximate estimates but cannot account for within-study variability. Additionally, most studies evaluated early treatment phases and did not assess long-term stability or post-treatment relapse. Future research should focus on large-scale, multicentre trials with standardised measurement protocols, including CBCT or 3D photogrammetry, to evaluate aligner efficiency across different movement categories. Investigations into new materials, such as shape-memory polymers or multi-layer laminates, could improve force decay characteristics. The integration of machine learning algorithms into treatment planning software may optimise staging and predict outcomes based on patient-specific variables.

CONCLUSIONS

1. Distalization and rotational movements with clear aligners achieve approximately 75-78% of planned movement and can be considered reasonably predictable when attachments and careful staging are used.
2. Transverse expansion, tipping/torque, and overbite reduction exhibit moderate predictability (≈53-62%), necessitating overcorrection and vigilant monitoring.
3. Root torque, space closure, and vertical intrusion remain unreliable; mandibular incisor intrusion achieves only ≈9,5% of planned values, suggesting that hybrid treatment or skeletal anchorage may be required for significant vertical corrections.

4. Patient education and digital monitoring enhance adherence and satisfaction, mitigating transient pain and psychosocial impacts.
5. Further randomized controlled trials with larger cohorts and standardized protocols are needed to refine accuracy estimates and evaluate adjunctive techniques.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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