Efficacy of Clear Aligners in Controlling Tooth Movement - Overcoming the Limitations of Aligners in Orthodontics

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Abstract

AIM: To investigate the effectiveness of clear aligners in orthodontic treatments, focusing on rotations, vertical adjustments, and three-dimensional changes.

METHODS: A systematic review of the PubMed database was conducted using keywords related to clear aligners and orthodontic tooth movements. The search, limited to English-language articles published between 2009 and 2024, for subjects aged 19 and older, yielded 58 articles. After applying strict inclusion and exclusion criteria, 15 relevant articles were selected.

RESULTS: Rotational corrections for canines and premolars varied in accuracy, with distal rotations being more challenging. Rotations over 15° significantly reduced maxillary canine correction accuracy. Vertical movements showed higher accuracy in incisor extrusion and molar intrusion, being more effective at closing bites. No significant difference was found between Invisalign optimized and conventional attachments. Aligners supported mesiodistal and buccolingual movements and dental arch expansion, though these often involved tipping.

CONCLUSION: Clear aligners are effective for various orthodontic tooth movements, despite variability in predictability and outcomes. Improving results involves optimising attachment designs, frequent aligner changes, and personalised treatment plans. Clear aligners remain a promising orthodontic alternative, with ongoing research aimed at enhancing precision.

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1 Introduction

In 1945, a method using several aligners to correct crowded teeth was introduced by Kesling (Kesling, 1945). Later, a removable plastic retainer called Essix was introduced by Ponitz (Ponitz, 1971), which became more popular when combined with interproximal reduction (IPR) by Sheridan and colleagues in the 1990s (Sheridan et al., 1993).

A significant breakthrough occurred in 1997 when two students from Stanford University, Zia Chishti and Kelsey Wirth, along with a computer expert, established Align Technology in Palo Alto, CA, USA (Bouchez et al., 2010). Their new technology, called Invisalign, received approval from the Food and Drug Administration and was first presented at the American Congress of Orthodontists in 1999, before being introduced in Europe two years later.

Originally, Invisalign was designed for mild to moderate crowding and closure of small spaces (Joffe, 2003), but it has been improved over time to treat more complex cases involving major rotation of premolars, upper incisor torque, distalisation, and/or extraction space closure (Baldwin et al., 2008). Nowadays, it is one of the most popular choices for teeth alignment using clear aligners.

Invisalign claims to correct various tooth misalignments without the need for auxiliary methods. For example, it asserts the ability to rotate upper and lower central incisors by up to 40°, canines and premolars by up to 45°, lateral incisors by up to 30°, and molars by up to 20°. Additionally, it states that it can move anterior teeth labially or lingually by up to 2.5 mm, and posterior teeth by 4 mm and 2 mm, respectively. However, there is a paucity of published studies confirming the efficacy of all these claimed movements (Galan-Lopez, 2019).

Research has demonstrated the efficacy of clear aligners in achieving a wide range of tooth movements, including rotation, translation, intrusion, and extrusion. Kravitz et al. (2009) conducted a prospective clinical study evaluating the efficacy of tooth movement with Invisalign and found results comparable to traditional braces in terms of dental alignment and occlusal outcomes. Additionally, clear aligners offer several advantages, such as improved oral hygiene, reduced risk of soft tissue irritation, and enhanced patient compliance (Boyd et al., 2006).

However, despite their effectiveness, the predictability of clear aligners is generally considered to be lower in more challenging cases (Zheng et al., 2017), particularly those involving tooth extraction (Dai et al., 2019), open bite or deep bite exceeding 1.5 mm (Khosravi et al., 2017), or when precise root movements (such as torque and translational movements) are required (Jiang et al., 2021).

Several factors contribute to the limitations of clear aligners in orthodontic practice. One such factor is the lack of direct bonding between the aligner and the tooth surface, which can result in less predictable tooth movement (Lombardo et al., 2017). Unlike traditional braces, where brackets are directly bonded to the teeth, clear aligners rely on passive fit, potentially compromising the precision of tooth movement.

Furthermore, patient compliance plays a crucial role in the success of clear aligner therapy. Aligners must be worn for a minimum of 20 to 22 hours per day to achieve optimal results (Kravitz et al., 2009). Non-compliance or improper wear can lead to treatment delays, relapse, or suboptimal outcomes, underscoring the importance of patient education and motivation throughout the treatment process.

Moreover, clear aligners may be less effective in treating certain types of malocclusions, such as severe crowding or skeletal discrepancies, which may require adjunctive treatments or alternative approaches (Rossini et al., 2015). In such cases, interdisciplinary collaboration between orthodontists and other dental specialists may be necessary to develop comprehensive treatment plans that effectively address the underlying issues.

Despite these limitations, advancements in clear aligner technology continue to improve treatment outcomes and expand the scope of orthodontic correction. Novel materials, such as thermoplastic polymers with enhanced mechanical properties, offer improved force delivery and biomechanics, allowing for more precise tooth movement (Mai et al., 2017). Additionally, computer-aided design and manufacturing (CAD/CAM) technologies enable the fabrication of customised aligners with greater accuracy and efficiency, reducing the need for manual adjustments and refinements.

Innovations in treatment planning software have also enhanced the predictability of clear aligner therapy, allowing orthodontists to simulate tooth movements and anticipate treatment outcomes more accurately (Simon et al., 2018). By leveraging these technological advancements, orthodontists can optimise treatment planning and manage complex cases more effectively, ultimately improving the overall success rate of clear aligner therapy.

This review seeks to build upon existing literature by critically evaluating the efficacy of clear aligners in controlling tooth movement and exploring novel approaches to overcome the limitations associated with aligner therapy in orthodontics. By advancing our understanding of clear aligner therapy, this research aims to contribute to the optimization of orthodontic treatment modalities and improve patient outcomes.

2 Methods

The search strategy was formulated following the 'PICO' framework, which includes the components Population, Intervention, Comparison, and Outcome. A modified research question incorporating these PICO elements was developed to guide the systematic literature retrieval.

The population of interest comprised adult patients experiencing extrusion, intrusion, rotation, expansion, distalisation, and tipping. The intervention under investigation was the use of clear aligners. Comparisons were made between clear aligner therapy (CAT) without auxiliaries such as elastics and attachments, including overcorrection and staging, and CAT with auxiliaries and similar overcorrection or staging protocols. The primary outcome was defined as predictable tooth movements.

A systematic search was performed in the PubMed database utilising a combination of specific keywords and Boolean operators: (Clear Aligner OR Invisalign AND Orthodontic Tooth Movement OR Tooth Movement OR Orthodontics) AND (Clear Aligner OR Invisalign AND Efficacy OR Predictability) AND (Clear Aligner OR Invisalign AND Rotation OR Extrusion OR Extraction OR Torque OR Expansion). The search was restricted to articles published in English, involving subjects aged 19 years and older, and with publication dates from 1 January 2009 to 1 January 2024.

The inclusion criteria for the study encompassed both prospective and retrospective original research conducted on human subjects possessing permanent dentition, with a minimum chronological age of 15 years. Eligible studies specifically examined orthodontic treatments utilizing clear aligners and provided detailed descriptions of the materials and techniques employed. Furthermore, included investigations were required to feature appropriate statistical analyses to ensure the robustness of their findings.

Conversely, studies were excluded if they involved patients with genetic syndromes or severe facial malformations, or if they employed surgical orthodontic methods. Additional exclusions applied to case reports, review articles, abstracts, author debates, and summary articles. Research involving fewer than ten patients, animal studies, those irrelevant to the review question, or articles published more than fifteen years prior were also omitted.

These stringent criteria guided the screening process, ultimately leading to the selection of 19 relevant articles, of which 10 met all eligibility requirements. Subsequent manual searching of references identified 5 more pertinent studies, culminating in a total of 15 articles incorporated into the final analysis.

Finally, 15 articles fulfilled the inclusion criteria, and full texts were assessed. Six are prospective studies and nine are retrospective studies. The demographic characteristics of the articles are listed in supplementary **Table S1**. Sample sizes in individual studies ranged from 20 to 150 patients, with a total of 951 patients. The age at the start of aligner treatment in the evaluated sample ranged from 18 to 75 years.

2.1 Statistics

Descriptive statistics, frequency analysis, and content analysis were employed as part of the qualitative methodology to systematically analyze the textual content of the included studies. It is important to note that, given the narrative nature of this study, regression analysis and meta-analysis techniques were not deemed suitable for the analytical framework.

3 Results

3.1 Biomechanical movements

Rotation. Rotation in orthodontics refers to the repositioning of a tooth along its longitudinal axis. It commonly occurs when a tooth is misaligned or turned out of its proper position. Rotation can be mesial or distal, and its correction is essential for achieving optimal occlusion and aesthetics in orthodontic treatment.

Mesial rotation involves the movement of a tooth in such a way that the crown of the tooth rotates towards the mesial (front) direction while the root moves distally (backwards). This movement can be seen when a tooth is tilted or rotated towards an adjacent tooth or towards the midline of the dental arch. Mesial rotation typically results in the crown of the tooth moving more towards the front of the mouth compared to the root.

Distal rotation, on the other hand, is the opposite movement where the crown of the tooth rotates towards the distal (back) direction while the root moves mesially (towards the front). This type of rotation causes the tooth to tilt or rotate away from an adjacent tooth or away from the midline of the dental arch towards the back of the mouth. Distal rotation results in the crown of the tooth moving more towards the back of the mouth compared to the root.

Vertical movements. Extrusion in orthodontics refers to the process of moving a tooth in the vertical direction away from the jawbone. This movement aims to lengthen the tooth's position in the dental arch. Orthodontic appliances gradually extrude teeth to their desired height, correcting bite issues and improving overall dental alignment.

Intrusion in orthodontics involves the vertical movement of a tooth towards the jawbone, reducing its height in the dental arch. This corrective action is crucial for addressing issues such as overbite or deep bite. Orthodontic appliances, like braces or clear aligners, apply controlled forces to gradually intrude teeth, optimising occlusion and enhancing overall dental alignment and aesthetics.

Horizontal movements. Dental expansion, or orthodontic expansion, is the widening of the dental arch to create additional space or correct narrow dental arches. This process involves applying controlled forces to expand the upper or lower jaw, allowing for proper alignment of the teeth and improved bite function. Orthodontic appliances such as palatal expanders or clear aligners facilitate gradual expansion, enhancing overall dental aesthetics and occlusal harmony.

Mesiodistal movement involves shifting a tooth along the horizontal axis towards or away from the midline of the dental arch, while buccolingual movement pertains to the tooth's displacement towards the cheek or tongue side. Distalisation, specifically, refers to the movement of a tooth away from the midline. These movements are crucial in orthodontic treatment for correcting tooth alignment and achieving proper occlusion.

3.2 Predictability outcome measurement methods

Quantitative measurements of predicted and achieved tooth movements were primarily conducted using the Invisalign ClinCheck system. Digital models of all teeth, ranging from the central incisor to the second molar, were generated from intraoral scans. Predicted values were derived by overlaying the initial and final ClinCheck models, while achieved values were determined by overlaying the initial ClinCheck models with digital models from the post-treatment scan (**Figure 1**). Individual teeth were superimposed using a best-fit analysis method for accurate measurement. The tooth movements assessed included mesial-distal crown tip, buccal-lingual crown tip, intrusion, extrusion, and rotation.

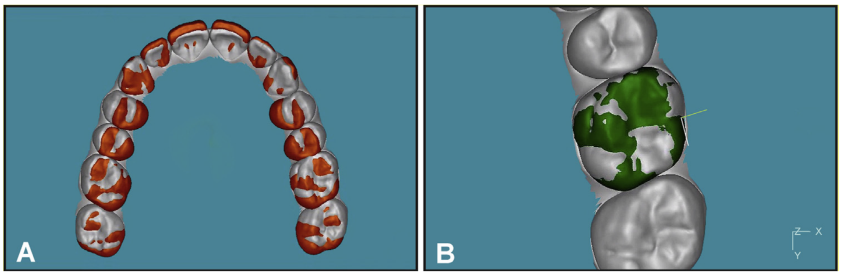

Figure 1. A) Determining the achieved values. Global alignment of initial ClinCheck model (orange) over the posttreatment model (white). B) Superimposition of a segmented tooth from the initial ClinCheck model (green) over the unsegmented posttreatment model (white) using a best-fit surface registration. Source: Haouili et al., 2020.

To determine the accuracy of these movements, the percentage accuracy was calculated using the following formula:

$$\text{Percentage of Accuracy} = 100\% \times \frac{\text{predicted}-\text{achieved}}{\text{predicted}}$$

This equation accounted for directionality and ensured that the percentage accuracy did not exceed 100% for teeth that achieved movements beyond their predicted values.

Pre- and post-treatment lateral cephalometric radiographs were imported (Dolphin Imaging software) to assess changes during treatment. Linear and angular measurements were taken during the assessment. To evaluate treatment changes, measurements were made on nine linear and three angular parameters (**Figure 2**), using palatal, occlusal, and mandibular planes as reference lines (Khorsavi et al., 2017).

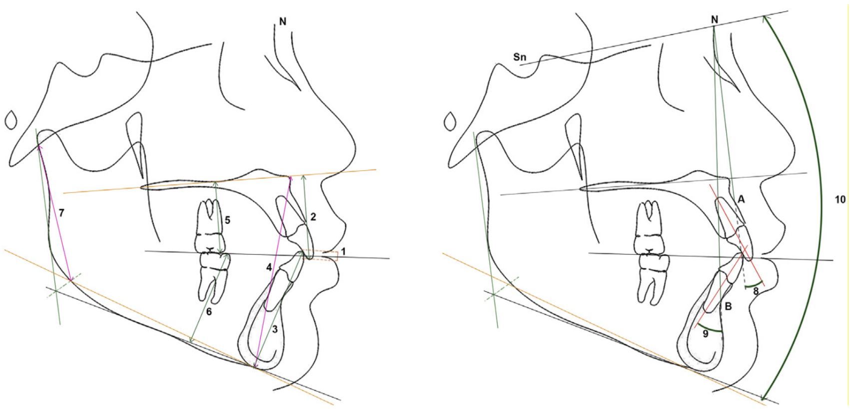

Figure 2. Linear (left) and angular (right) cephalometric measurements were used to assess the anterior and posterior vertical dimension changes in patients who underwent orthodontic treatment with the Invisalign appliance. A, Linear measurements: 1, overbite; 2, maxillary incisor tooth tip to palatal plane; 3, mandibular incisor tooth tip to mandibular plane; 4, anterior facial height; 5, maxillary molar mesial cusp tip to palatal plane; 6, mandibular molar mesial cusp tip to mandibular plane; 7, posterior facial height. B, Angular measurements: 8, maxillary incisor axis to nasion-A point; 9, mandibular incisor axis to nasion-B point; 10, mandibular plane angle. Source: Khorsavi et al., 2017.

For assessing anterior vertical changes, measurement was performed on specific linear dimensions: overbite (the shortest vertical distance between maxillary and mandibular incisor tips perpendicular to the occlusal plane), vertical incisor position (distance between incisors and palatal or mandibular planes), and anterior facial height (distance from the anterior nasal spine to the menton). Angular measurements included the angle of maxillary and mandibular incisors relative to specific cranial landmarks.

The DICOM (Digital Imaging and Communications in Medicine) data of the CBCT and STL files of digital models were used to analyse expansion movement (Zhou and Guo et al., 2020). Pretreatment and post-expansion phase records were gathered, which included digital models and cone-beam computed tomography scans. Data analysis was performed using Dolphin 3D, Geomagic Studio 12.0, and Meazure software to measure and compare the expected treatment outcomes with the actual results.

3.3 Parameters that influence predictability

Firstly, the severity of malocclusion plays a significant role. The complexity and extent of malocclusion, including severe crowding, spacing, rotations, and skeletal discrepancies, can present challenges in achieving the desired tooth movements with clear aligner treatment.

Patient compliance is another critical factor. Wearing aligners as instructed by the orthodontist is essential for successful treatment outcomes; irregular wear or non-compliance can impede progress and negatively affect predictability.

The treatment plan and strategy also impact predictability substantially. The clarity and precision of the treatment plan established by the orthodontist, which includes accurate diagnosis, digital treatment planning, and the selection of appropriate aligner attachments and auxiliaries, are vital components for effective clear aligner therapy.

Moreover, the quality of the aligners influences treatment success. The fit and material integrity of the aligners determine their ability to apply controlled forces necessary for accurate tooth movement. Poorly fitting aligners or material degradation may compromise treatment predictability.

Attachment design and placement further contribute to treatment outcomes. Carefully designed and optimally placed attachments on teeth facilitate specific movements and enhance the control of tooth movements, thereby improving predictability.

Interproximal reduction (IPR), or enamel reduction between teeth, may be required to create space for alignment. When properly performed, IPR can aid in achieving predictable tooth movements and optimise treatment outcomes.

Additional auxiliary mechanics, such as elastics or buttons used alongside clear aligners, can also influence predictability by facilitating specific tooth movements or correcting bite discrepancies.

Finally, regular monitoring of treatment progress and making necessary adjustments throughout the course of therapy are essential. This process may involve refinements or mid-course corrections to address any deviations from the initial treatment plan, thereby improving overall predictability.

3.4 Auxiliaries used with clear aligner therapy

Attachments are small, tooth-coloured bumps or ridges that are placed strategically on specific teeth during clear aligner treatment. These may include Invisalign attachments, also known as SmartForce®, or conventional attachments associated with other aligner systems. Attachments serve as anchor points for the aligners, allowing for more precise and predictable tooth movements. By providing additional grip and leverage, they enhance the aligners' ability to exert controlled forces on the teeth, thereby facilitating complex movements such as rotations, extrusions, and intrusions. These attachments are custom-designed according to the individual patient's treatment plan and are typically fabricated from tooth-coloured composite materials to blend seamlessly with the natural dentition, ensuring minimal visibility during wear.

A bite ramp, sometimes referred to as an intrusion ramp or occlusal ramp, is a small raised area or incline placed on the surface of certain teeth to assist in correcting bite issues during orthodontic treatment. This device functions by guiding the positioning of the jaw and reducing excessive vertical overlap between the upper and lower teeth, helping to alleviate conditions such as deep bites or overbites.

Power ridges are specialised features incorporated into clear aligners to facilitate targeted tooth movements during orthodontic therapy. These ridges are small, raised areas located on the surface of the aligner material and are generally positioned vertically on the teeth requiring correction. By exerting focused pressure, power ridges aid in achieving rotational movements, extrusions, or intrusions as needed to properly align the dentition. Consequently, they enhance the effectiveness of clear aligners in managing complex malocclusions and in attaining the desired treatment outcomes.

Interproximal reduction (IPR), also known as tooth stripping or slenderizing, is a technique used to create space between teeth by removing small amounts of enamel from the sides of adjacent teeth. Typically performed using fine abrasive strips or discs, this procedure allows for precise and controlled enamel removal to achieve the necessary interproximal space. IPR is frequently employed to relieve crowding, correct tooth alignment, and facilitate tooth movement during orthodontic therapy, including clear aligner treatment. By generating adequate space, IPR promotes more effective tooth alignment, often reducing the need for tooth extraction and contributing to a harmonious occlusion.

Orthodontic elastics, commonly referred to as rubber bands, are essential components in orthodontic treatment that assist in correcting malocclusions and aligning jaws. Made from latex or synthetic materials, these bands apply gentle, continuous forces to teeth or jaws to guide them into proper alignment. They are attached to brackets or hooks on braces and are available in a variety of sizes and colours. Elastics help close gaps, align dental arches, and improve occlusal harmony. For optimal results, consistent wear as prescribed by the orthodontist is crucial; non-compliance can lead to delays in treatment or suboptimal outcomes. Overall, orthodontic elastics play a vital role in achieving healthy and functional smiles.

3.5 Clinical trial results

Rotation. Clear aligners have emerged as a popular orthodontic treatment modality for correcting tooth rotations. The following studies investigated the efficacy of clear aligners in achieving rotational tooth movement (**Table S2**).

Lione et al. (2022) reported a significant post-treatment improvement in the rotation of upper first molars, assessed using Henry's angle (the angle formed between the midpalatal raphe and a line passing through the mesiobuccal and distobuccal cusps of the upper molar), with a mean reduction of 7.37° ($p < 0.001$). Despite initial angles exceeding 11°, clear aligner therapy effectively corrected the rotation, demonstrating its efficacy in addressing moderate to severe rotations.

Kravitz et al. (2009) examined rotations in maxillary and mandibular canines categorised by the degree of rotation. They found that clear aligners achieved significant improvements in rotation for both maxillary and mandibular canines, with mean accuracies ranging from 18.8% to 35.8% ($p < 0.05$).

Investigating premolar rotations, Simon et al. (2014) observed significant improvements with clear aligner therapy. However, they noted a lower mean accuracy for rotations exceeding 15° compared with those below 15° (23.6% versus 43.3%, $p < 0.05$). This suggests that while clear aligners can effectively correct mild to moderate rotations, they may be less predictable for more severe cases.

In a study of right and left first molars, Morales-Burruezo et al. (2020) evaluated rotational changes with clear aligners and observed significant post-treatment improvements for both right and left molars ($p < 0.001$). Subgroup analysis based on the presence of cross-bite revealed differences in the efficacy of rotational correction, emphasising the importance of individualised treatment approaches.

Rotational accuracy. The accuracy of rotation in orthodontic tooth movement, comparing actual and planned movements, varied across studies and tooth types (**Table S3**).

In their investigation of upper first molars, Lione et al. (2022) reported a mean post-treatment rotation of $11.06° \pm 3.16$, compared with a planned rotation of $9.05° \pm 2.41$. This difference of 2.01° was statistically significant ($p < 0.001$), with an overall accuracy of 82%.

Simon et al. (2014) assessed the accuracy of rotation in upper premolars categorised by the degree of rotation. They found that rotations exceeding 15° exhibited lower mean accuracy (23.6%) compared with rotations less than 15° (43.3%), suggesting that larger rotations present greater challenges in achieving accurate tooth movement.

Castroflorio et al. (2023) analysed a range of teeth and observed significant discrepancies between actual and planned rotations. For example, maxillary central incisors showed a mean post-treatment rotation of 7.33° ± 6.03 versus a planned rotation of 2.77° ± 2.27 ($p < 0.001$). Similar significant differences were reported for maxillary lateral incisors, canines, premolars and molars, as well as for mandibular incisors, canines, premolars and molars.

Kravitz et al. (2009) investigated rotational accuracy across various maxillary and mandibular teeth and observed that mean accuracies varied by tooth type and degree of rotation. Notably, teeth with rotations exceeding 15° demonstrated substantially lower mean accuracies than those with rotations below 15°.

Haouili et al. (2020) examined rotational accuracy in both maxillary and mandibular teeth, classifying rotations as mesial or distal. They found significant differences in mean accuracies between tooth types and rotation directions. For instance, mesial rotations of maxillary canines exhibited higher mean accuracy (51.5%) than distal rotations (37.2%). Comparable significant differences were observed for other tooth types and rotation directions, emphasising the importance of considering tooth type and rotation direction when assessing rotational accuracy.

Morales-Burruezo et al. (2020) evaluated rotation accuracy in right and left first molars and reported a mean difference of 0.54° ± 3.05 for the right first molar and −0.34° ± 3.57 for the left first molar; the difference for the left first molar was not statistically significant ($p = 0.309$). The reported overall accuracies were 80.4% for the right first molar and 115.3% for the left first molar.

In a comparison of optimised versus conventional rotation attachments, Karras et al. (2020) identified significant differences in rotational accuracy for several teeth. For example, the mean difference in rotation for maxillary canines with optimised attachments was 4.94° ± 6.62, compared with 4.45° ± 4.59 for conventional attachments ($p < 0.05$). Similar significant differences were observed for maxillary premolars, mandibular canines and mandibular premolars.

Factors influencing rotational accuracy. The accuracy of rotation in orthodontic tooth movement is influenced by multiple factors, as evidenced by the findings of several studies (**Table S4**).

A study of premolar derotation found that the presence of attachments significantly affected rotational accuracy. Premolars derotated by more than 10° with attachments exhibited a mean accuracy of 37.5%, compared with 42.4% without attachments ($p < 0.001$). When derotation angles were categorised, rotations greater than 1.5° had lower mean accuracy than those less than 1.5° (23.2% vs. 41.8%) (Simon et al., 2014).

Castroflorio et al. (2023) investigated the impact of attachment type and aligner-change frequency on rotation accuracy. They reported that conventional attachments yielded a mean accuracy of 0.09, whereas optimised attachments showed a mean accuracy of 0.03. Additionally, aligner-change frequency influenced predictability: a decrease of 12% was observed when aligners were changed every 7–10 days ($p = 0.23$), and a significant effect was noted with continuous aligner change ($p < 0.001$).

In a comparison of optimised and conventional attachments, Karras et al. (2020) found no statistically significant difference in mean accuracy between the two attachment types for canine and premolar rotation ($p = 0.0638$). However, there was a trend toward higher accuracy with optimised attachments ($7.3° \pm 26.4$) compared with conventional attachments ($1.61° \pm 6.11$, $p = 0.0533$).

Kravitz et al. (2009) observed varying mean accuracies for canine rotation depending on the degree of rotation, with significantly lower accuracies for rotations exceeding 15° ($p < 0.05$). Haouili et al. (2020) reported significant differences in accuracy between distal and mesial rotation of maxillary canines ($p < 0.05$). Similarly, Palone et al. (2022) described variable accuracies across different rotation magnitudes, with lower incisors, upper canines and premolars demonstrating higher mean accuracy at smaller rotation angles than at larger angles ($p < 0.05$).

Overall, these findings highlight the multifactorial nature of rotational accuracy in orthodontic tooth movement and emphasise the importance of considering attachment type, aligner-change frequency and the degree of rotation for optimal treatment outcomes.

Expansion. Clear aligner therapy has demonstrated efficacy in achieving dental expansion across various tooth types. The following studies have investigated expansion with clear aligners (**Table S5**).

Lione et al. (2022) evaluated mesial and distal buccal expansion of the upper first molars, as well as expansion of canines, premolars and molars. Significant increases in mesial and distal buccal expansion were observed post-treatment, with mean differences ranging from 1.5 to 3.45 mm ($p < 0.001$). Additionally, clear aligners effectively expanded canines, premolars and molars, indicating their capacity to achieve multi-tooth expansion.

Duncan et al. (2015) assessed expansion of canines, premolars and molars across varying degrees of crowding severity. They reported significant increases in tooth widths post-treatment for all crowding categories (mild, moderate and severe), with mean differences ranging from 1.2868 to 3.1952 mm ($p < 0.0001$). These results indicate that clear aligners can address crowding by producing dental expansion.

Lione et al. (2021) evaluated linear and angular measurements to assess dental expansion with clear aligners. Significant increases in intercanine width, inter-premolar width, intermolar width and crown angulation were observed post-treatment ($p < 0.001$). These findings indicate that clear aligners can achieve both linear and angular expansion, contributing to comprehensive dental alignment.

Expansion accuracy. Clear aligner therapy aims to achieve specific tooth movements as planned; however, discrepancies between planned and actual movements can occur. The accuracy of expansion with clear aligners was evaluated across multiple studies (**Table S6**), as summarised below.

Lione et al. (2022) investigated the accuracy of expansion in upper first molars. They found minimal differences between post-treatment and planned measurements for mesial and distal buccal expansion, with mean differences ranging from 0.10 to 0.11 mm ($p > 0.5$). This high level of agreement suggests precise control over expansion outcomes with clear aligners, with an accuracy rate of 99%.

Morales-Burruezo et al. (2020) assessed expansion accuracy in canines, premolars and molars. Significant differences were observed between post-treatment and planned measurements for all analysed teeth ($p < 0.001$). Despite these differences, the accuracy rates ranged from 65.2% to 81%, indicating a relatively high level of precision in achieving expansion objectives with clear aligners.

Zhou et al. (2020) analysed expansion accuracy in canines, premolars and molars. They found significant differences between post-treatment and planned measurements for all teeth ($p < 0.05$). However, the accuracy rates ranged from 68.31% to 79.25%, suggesting effective control over expansion outcomes with clear aligners despite some discrepancies.

Krieger et al. (2012) examined the accuracy of expansion in upper anterior arch length and intercanine distances. They reported minimal differences between post-treatment and planned measurements, with mean differences ranging from -0.19 to 0.13 mm. While these differences were statistically significant ($p < 0.05$), they were clinically negligible. The study demonstrated high accuracy in achieving expansion goals with clear aligners, with confidence intervals indicating precision in treatment outcomes.

Lione et al. (2021) evaluated linear measurements of expansion across various dental dimensions. They found statistically significant differences between post-treatment and planned measurements for intercanine width ($p < 0.05$). However, the mean differences were clinically minor, ranging from 0.3 to 1.6 mm. These findings suggest that clear aligners can achieve expansion objectives with a high degree of accuracy, as indicated by the reported confidence intervals.

Houle et al. (2017) investigated the accuracy of expansion in multiple dental parameters, including interpremolar and intermolar widths, as well as canine and premolar tip and gingival positions. They reported statistically significant differences between post-treatment and planned measurements for most parameters ($p < 0.05$). Despite these differences, the accuracy rates ranged from 52.9% to 100%, indicating effective control over expansion outcomes with clear aligners.

In conclusion, expansion with clear aligners predominantly involves a tipping movement, with the ratio of root-to-crown expansion approximately 2:5 (Zhou et al., 2020). The rate of expansion is greater in the premolar region (1.57–3.8 mm) than in the canine (1.28–1.74 mm) and molar (1.65–2.65 mm) regions, depending on the severity of crowding (Duncan et al., 2015).

Bucco-lingual and mesio-distal tipping. Clear aligner therapy has demonstrated efficacy in achieving bucco-lingual and mesio-distal movement across various tooth types. The following studies have investigated bucco-lingual and mesio-distal movement with clear aligners (**Table S7**).

Lione et al. (2022) examined the efficacy of clear aligners in inducing bucco-lingual and mesio-distal movement in upper first molars. The pre-treatment measurement for mesial buccal sagittal (MS) movement was 29.3 ± 2.2, which significantly increased to 30.3 ± 2.5 post-treatment, indicating a mean difference of 1.0 ($p < 0.001$). Similarly, for distal buccal sagittal (DS) movement, the pre-treatment measurement was 24.3 ± 2.1, which significantly increased to 25.2 ± 2.5 post-treatment, with a mean difference of 0.9 ($p < 0.001$).

Morales-Burruezo et al. (2020) investigated inclination changes in the right and left first molars. Both the right and left first molars exhibited significant changes in inclination post-treatment compared with pre-treatment values. For the right first molar, inclination changed from -7.77 ± 8.49 pre-treatment to -5.51 ± 8.08 post-treatment, with a mean difference of 2.26 ($p < 0.001$). Similarly, the left first molar changed from -6.54 ± 8.26 pre-treatment to -4.41 ± 7.62 post-treatment, with a mean difference of 2.13 ($p < 0.001$).

Subgroup analysis based on the presence of cross-bite revealed significant differences in inclination changes between groups. The cross-bite group exhibited greater changes than the no cross-bite group for both the right ($p = 0.039$) and left ($p = 0.002$) first molars.

Tipping accuracy. The accuracy of bucco-lingual and mesio-distal movements with clear aligners has been assessed by various researchers (**Table S8**), providing valuable insights into the efficacy of orthodontic treatment.

Lione et al. (2022) investigated the accuracy of mesial buccal sagittal (MS) and distal buccal sagittal (DS) movements in upper first molars. Post-treatment MS movement measured 30.3 ± 2.5, closely aligning with the planned treatment of 31.2 ± 2.3, yielding a mean difference of 0.9 ($p > 0.5$), with an accuracy of 97%. Similarly, DS movement exhibited high accuracy, with a mean difference of 0.7 ($p > 0.5$) and an accuracy of 97%.

Haouili et al. (2020) explored accuracy across various teeth and movements. For instance, the accuracy of mesial and distal tip movements ranged from 47.8% to 64.7% and from 43.8% to 62.9%, respectively.

Morales-Burruezo et al. (2020) assessed the accuracy of mesio-distal movement in the right and left first molars. The observed mean differences between post-treatment and planned treatment were -0.42 and -0.88, respectively, with corresponding accuracies of 123.5% and 170.4%.

Ravera et al. (2016) investigated upper first molar distalisation accuracy. The mesiobuccal cusp showed no significant difference in vertical and tipping movement ($p = 0.43$ and $p = 0.27$, respectively), with mean deviations of 2.2 mm and 2.03 mm at the centre of the crown.

Castroflorio et al. (2023) assessed mesio-distal and bucco-lingual translation in various teeth. They reported significant differences between post-treatment and planned treatments, indicating accurate movement execution ($p < 0.001$).

Kravitz et al. (2009) reported accuracy percentages for different tooth types and movements, showing variations in accuracy across maxillary and mandibular teeth.

Factors influencing tipping accuracy. Several factors influence the accuracy of bucco-lingual and mesio-distal movements during orthodontic treatment with clear aligners, as highlighted by various studies (**Table S9**).

Simon et al. (2014) investigated the effect of attachments on distalisation accuracy. They found that distalisation with optimised attachments resulted in significantly higher mean accuracy (88.4%) compared with distalisation with conventional attachments (86.9%). Moreover, the absence of attachments led to a slightly lower mean accuracy. These findings suggest that optimised attachments can enhance the accuracy of tooth movement during distalisation.

Castroflorio et al. (2023) explored the impact of attachment optimisation and aligner-change frequency on movement accuracy. They discovered that aligner-change frequency significantly influenced predictability, with a decrease in predictability observed with more frequent aligner changes. However, the use of optimised attachments improved accuracy compared with conventional attachments, indicating their potential to enhance treatment outcomes.

Palone et al. (2022) investigated the influence of tooth inclination and angulation on movement accuracy. They found that incisor inclination $\geq 12.2°$ and canine angulation

$> 10.1°$ resulted in significantly higher mean accuracy than their respective counterparts. Additionally, lower incisors, premolars, and molars with reduced angulation exhibited higher accuracy. This suggests that aligners may be more effective in achieving accurate tooth movements within specific inclination and angulation ranges.

In conclusion, Kravitz et al. (2009) found that lingual crown-tip adjustments of mandibular incisors exhibited higher accuracy (54.8%) compared with labial crown-tip adjustments of maxillary incisors (37.6%).

Furthermore, Haouili et al. (2020) reported that the distal crown-tip of the maxillary second molar (63%) is more accurate than that of the mandibular second molar (50%), and that the buccal crown-tip of the mandibular second premolar (70%) is significantly more accurate than that of the maxillary second premolar (61%).

Vertical movements. Vertical movement plays a crucial role in orthodontic treatment, influencing various dental and facial parameters. Studies have examined the effects of clear aligners on vertical movement across different bite patterns.

In patients with a normal overbite, Khosravi et al. (2016) observed significant changes in incisor position and anterior facial height after treatment. The overbite decreased by 0.4 mm (mean difference -0.4 mm), and anterior facial height increased by 0.7 mm. There were also changes in incisor inclination and molar position, although not all were statistically significant.

Patients with a deep bite exhibited notable alterations in vertical parameters. The overbite decreased by 1.6 mm (mean difference -1.6 mm), accompanied by changes in incisor and molar positions. The mandibular incisors showed a significant increase in inclination (mean difference 2.5 degrees). These findings suggest that clear aligners can effectively address deep-bite issues by modifying vertical parameters.

In individuals with an open bite, vertical changes were evident though less pronounced. The overbite increased by 1.3 mm after treatment, indicating successful correction of the open bite. Significant changes were also observed in mandibular incisor inclination and molar position, emphasising the effectiveness of clear aligners in vertical correction for open-bite cases.

Accuracy of vertical movements. The accuracy of vertical tooth movement with clear aligners is a crucial aspect of orthodontic treatment planning and execution. Various studies have investigated the discrepancy between planned and actual movements to evaluate the effectiveness of clear aligner therapy (**Table S10**).

Kravitz et al. (2009) conducted a comprehensive analysis of prescribed versus achieved movements across different tooth types. They found significant discrepancies between the planned and actual movements for maxillary and mandibular incisors, laterals and canines. The lack of correction (mLC) ranged from 32.5% to 56.4% for different tooth types, highlighting the variability in achieving the desired vertical movement.

Castroflorio et al. (2023) assessed vertical translation in various teeth using clear aligners. They reported significant differences between planned and post-treatment positions for maxillary and mandibular incisors, premolars and molars. The lack of correction was consistently observed across different tooth types, indicating the challenges in accurately predicting vertical movement with clear aligners.

Haouili et al. (2020) further investigated the accuracy of intrusion and extrusion in different tooth types. They found significant discrepancies between planned and achieved movements for both maxillary and mandibular teeth. The lack of correction ranged from 35.1% to 63.1% for different tooth types, suggesting that vertical movement with clear aligners may be difficult to control precisely.

Krieger et al. (2012) found that the mean accuracy of vertical movement was -0.71 ± 0.87 mm, indicating a slight overcorrection of planned movements.

Karras et al. (2020) compared the accuracy of optimised and conventional extrusion attachments in achieving vertical tooth movement. They observed significant improvements in accuracy with optimised attachments compared with conventional ones; however, discrepancies between planned and actual movements were still evident, indicating the complexity of achieving precise vertical tooth movement with clear aligners.

Factors influencing vertical accuracy. In assessing the accuracy of actual versus planned tooth movement in vertical movement with clear aligners, several studies shed light on the efficacy of various auxiliary techniques and staging/overcorrection approaches (**Table S11**).

Karras et al. (2020) compared the effectiveness of optimised and conventional attachments in achieving incisor and canine extrusion. They found a mean accuracy of 0.14 ± 0.42 mm, with a slight but statistically insignificant difference between the two attachment types (p = 0.0523). Similarly, Castroflorio et al. (2023) observed improved accuracy with optimised attachments compared to conventional ones (p = 0.03). Notably, the frequency of aligner changes significantly influenced predictability, with a decrease in accuracy observed at the 7- or 10-day interval compared to a constant change schedule ($p < 0.001$).

Palone et al. (2022) investigated the accuracy of upper canine and premolar intrusion, as well as incisor intrusion, categorised by the extent of movement. They reported mean accuracies ranging from 0.04 mm to 0.20 mm, with statistically significant differences observed across different levels of intrusion ($p < 0.001$ to $p = 0.002$).

Khosravi et al. (2017) employed various strategies to address different bite conditions, including normal overbite, deep bite and open bite. Techniques such as the use of virtual bite ramps, extrusion attachments on anterior teeth, and overcorrection of overbite were implemented to optimise outcomes. Additionally, Ravera et al. (2016) examined the influence of class II elastics and composite attachments on tooth movement accuracy, reporting significant findings ($p < 0.05$).

Overall, these studies underscore the importance of auxiliary techniques, attachment types and treatment protocols in achieving accurate vertical tooth movement with clear aligners. While some variation exists in the effectiveness of different approaches, optimising attachment design and treatment planning strategies can enhance the predictability and precision of orthodontic outcomes.

4 Discussion

This review aimed to evaluate the predictability and effectiveness of clear aligners in orthodontic tooth movements, including rotation, vertical movement, expansion, and mesiodistal (M-D) and bucco-lingual (B-L) movements. A comprehensive search in the PubMed database using specific keywords yielded 58 publications. After applying filters and adhering to the 'PICO' criteria, 19 relevant articles were identified, with 10 meeting the inclusion criteria. Additionally, a manual search of references found 5 more relevant articles, resulting in a total of 15 articles included for in-depth analysis of current evidence and practices.

It is true that, despite the advancements in clear aligner technology and the broadening range of treatment indications, achieving perfect predictability in all planned movements during orthodontic treatment with clear aligners is not guaranteed. Research has shown that the average accuracy of clear aligner treatment typically falls within the range of 41% to 73% (Kravitz et al., 2009; Haouili et al., 2020; Simon et al., 2014). This variability in accuracy can be attributed to several factors, such as the complexity of the movements required, the magnitude of those movements, and the specific characteristics of the teeth being treated. It highlights the importance of thorough planning and assessment by orthodontic professionals to maximise the effectiveness of clear aligner treatment.

4.1 Predictability of rotations

In the discussion of tooth derotation within the context of clear aligner treatment, several factors affect the effectiveness of achieving the desired outcomes. Clear aligners are custom-made, removable trays designed to apply controlled forces to move teeth gradually. While they are effective for addressing various malocclusions, achieving precise rotational movements poses unique challenges. Tooth rotations involve complex biomechanical processes influenced by factors such as attachment design, aligner material properties, and patient compliance.

Simon et al. (2014) and Nanda's principles of biomechanics (Principles and Biomechanics of Aligner Treatment, Chapter 2) underline the challenges posed by cylindrical tooth derotation due to the tendency of thermoplastic aligners to slip off round tooth surfaces, resulting in incomplete rotation and loss of tracking. Well-designed attachments, as emphasized by Simon et al. (2014) and Nanda's principles (Principles and Biomechanics of Aligner Treatment, Chapter 2), can enhance retention and provide a more active surface area for effective tooth movement.

Several studies have investigated the efficacy of clear aligners in correcting tooth rotations, providing valuable insights into treatment outcomes. For instance, Kravitz et al. (2009) examined rotation corrections in maxillary and mandibular canines and observed significant improvements in rotation for both tooth types. However, they noted variations in accuracy based on the degree of rotation, with rotations exceeding 15° exhibiting lower mean accuracies. Similarly, Simon et al. (2014) focused on premolar rotations and found that clear aligners effectively corrected rotations below 15° but were less predictable for rotations exceeding 15°. This highlights the importance of considering the severity of rotation when planning clear aligner treatment. In a more recent study, Lione et al. (2022) evaluated rotation corrections in upper first molars and reported significant improvements post-treatment. However, they noted variations in accuracy depending on the initial angle of rotation, with moderate to severe rotations demonstrating slightly lower mean accuracies.

Various factors influence the accuracy of rotation correction with clear aligners, including attachment type, aligner change frequency, and the direction of rotation. Castroflorio et al. (2023) investigated the impact of attachment type on rotation accuracy and found that optimized attachments yielded slightly higher mean accuracies compared to conventional attachments. However, the differences were not always statistically significant, suggesting that both attachment types can be effective in achieving rotation corrections. To enhance the predictability of tooth rotation movements with clear aligners, several strategies can be employed. Firstly, refining attachment designs to optimize grip and control can improve the accuracy of rotation corrections. Karras et al. (2020) compared optimized and conventional attachments and found that while both attachment types were effective, there was a trend towards higher accuracy with optimized attachments.

Aligner change frequency is another critical factor affecting treatment outcomes. Frequent aligner changes may improve predictability by ensuring continuous force application and minimising aligner deformation. Castroflorio et al. (2023) reported that aligner change frequency influenced rotation accuracy, with a significant improvement observed with constant aligner change protocols.

Furthermore, the direction of rotation plays a role in determining the predictability of tooth movements. Haouili et al. (2020) found significant differences in accuracy between mesial and distal rotations of maxillary and mandibular teeth. Mesial rotations generally exhibited higher mean accuracies compared to distal rotations, highlighting the asymmetrical nature of tooth movement.

Additionally, individualising treatment plans based on the degree and direction of rotation is essential for optimising outcomes. Clinicians should carefully assess the complexity of each case and tailor treatment strategies accordingly. For instance, rotations exceeding 15° may require additional biomechanical considerations and close monitoring during treatment.

Moreover, patient compliance plays a crucial role in achieving optimal rotation corrections. Educating patients about the importance of wearing aligners as prescribed and maintaining good oral hygiene habits can enhance treatment outcomes. Regular follow-up appointments allow clinicians to monitor progress, address any concerns, and make necessary adjustments to the treatment plan.

Moving forward, further research is needed to refine attachment designs, optimise treatment protocols, and enhance patient compliance. By addressing these factors, clinicians can improve the predictability and precision of tooth rotation movements with clear aligners, ultimately leading to better treatment outcomes for patients with malocclusions involving tooth rotations.

4.2 Predictability of expansion

The correction of transverse deficiencies through dental arch expansion remains a challenging aspect of clear aligner orthodontic treatment. Clinicians commonly resort to overcorrection during 3D treatment planning to address this challenge effectively (Houle et al., 2017; Lione et al., 2021).

Lione et al. (2022) and Duncan et al. (2015) provide evidence of successful expansion with clear aligners, with mean differences ranging from 1.5 to 3.45 mm ($p < 0.001$). Moreover, linear and angular measurements assessed by Lione et al. (2021) further confirm the capability of clear aligners to achieve both linear and angular expansion, contributing to comprehensive dental alignment.

Orthodontic aligners, characterised by their horseshoe-shaped geometry, administer expansive forces in a manner that yields an anteroposterior decreasing force gradient, resulting in diminishing efficacy of upper arch expansion, particularly from the first premolars to the second molars (Principles and Biomechanics of Aligner Treatment, Chapter 2). This observation is echoed by Houle et al. (2017), who highlighted a decrease in the accuracy and efficiency of expansion as the movement progresses posteriorly within the arch. Nearly half of the planned changes at the gingival margin of the upper first molars did not occur, with only 1.42 mm out of the intended 3.02 mm achieved. Similarly, at the cusp tip of the same tooth, only 0.77 mm out of the planned 3.28 mm was accomplished with the aligners, resulting in an accuracy of 76.6%. Overall, the upper first molars exhibited the lowest tracking accuracy. A noticeable trend emerged across the upper arch, indicating a decline in Clincheck accuracy moving posteriorly into the arch. This discrepancy is likely influenced by factors such as root anatomy, cortical plate thickness, increased mastication loading, and greater soft tissue resistance from the cheeks in the posterior region (Zhou and Guo et al., 2020).

Lione et al. (2021) observed a progressive decrease in expansion rate from the anterior to the posterior segments, resembling a “drawbridge expansion model”. Significantly greater expansion of maxillary width, measuring 3.5 mm at the first premolars and 3.8 mm at the second premolars, was observed, representing an average increase of 8.5% from initial values. This “drawbridge pattern” exhibited varying degrees of expansion in the canine (6.5%), premolar (8.5%), and posterior regions (5% for first molars, 1% for second molars), resulting in the transformation of the maxillary arch from a V-shape to a more parabolic form.

Despite the effectiveness of clear aligners in achieving tooth expansion, discrepancies between planned and actual movements may occur, affecting treatment accuracy. While studies such as those by Lione et al. (2022) demonstrate minimal differences between post-treatment and planned measurements, other studies, including Morales-Burruezo et al. (2020) and Zhou and Guo et al. (2020), report significant differences ($p < 0.001$). Factors contributing to these variations include the complexity of tooth movements, patient compliance, and the limitations of current aligner technology in fully controlling tooth movements.

While aligners possess the capability to widen the arch, this expansion primarily occurs through a tipping motion, with the ratio of expansion movement between the root and crown being approximately 2 : 5 (Zhou and Guo et al., 2020). To mitigate excessive tipping during maxillary expansion in digital planning, different buccal root torque should be added according to the amount of expansion. Lione et al. (2021) suggested planning for an additional 10° of buccal root torque in upper premolars and molars.

Zhou and Guo et al. (2020) revealed a negative correlation between the prescribed expansion amount and bodily expansion efficiency ($P < 0.05$). Consequently, in cases requiring significant expansion, clinicians are advised to decrease the expansion magnitude per aligner to safeguard periodontal health. Additionally, implementing more negative torque settings can enhance crown and root control, facilitating successful bodily expansion.

Moreover, the analysis indicated a negative correlation between initial torque and bodily expansion efficiency ($P < 0.05$). These findings underscore the importance of meticulous assessment of molar positioning in clinical practice. Specifically, when dealing with posterior teeth exhibiting pronounced buccal inclination, it is prudent to adjust expansion magnitudes accordingly and apply more negative crown torque. This approach helps prevent adverse occlusal effects resulting from excessive buccal inclination of posterior teeth. Furthermore, the study highlights the limitations of dental compensation for maxillary transverse deficiency, particularly in cases involving posterior teeth with substantial buccal inclinations. It suggests that traditional dental expansion treatments should be approached with caution in such instances to avoid exacerbating occlusal issues.

In summary, these findings offer valuable insights for clinical decision-making, emphasising the need for tailored treatment strategies based on individual patient characteristics and occlusal considerations. By optimising expansion protocols and torque settings, clinicians can achieve more predictable outcomes while minimising adverse effects on periodontal health and occlusion (Zhou and Guo et al., 2020).

Addressing factors contributing to discrepancies between planned and actual movements, such as patient compliance and aligner technology limitations, can lead to more accurate and predictable expansion outcomes with clear aligners.

4.3 Predictability of vertical movements

Among linear movements, vertical translation was identified as the most challenging when using aligners. Haouili et al. (2020) observed that the higher accuracy of incisor extrusion and molar intrusion, combined with the lower accuracy of incisor intrusion and molar extrusion, suggests that Invisalign is more effective in bite closure rather than bite opening. Khosravi et al. (2016) observed significant changes in incisor positions and anterior facial height post-treatment across different bite patterns, indicating the effectiveness of clear aligners in addressing vertical discrepancies.

Khosravi et al. (2017) deduced that correcting deep bite entails lower incisor proclination, upper incisor intrusion, and 0.5 mm of posterior extrusion. Conversely, rectifying open bite conditions involves incisor extrusion, with minimal alterations observed in molar vertical position and mandibular plane angle.

The discrepancy between planned and actual tooth movements with clear aligners can be attributed to several factors. Firstly, the inherent limitations of clear aligner technology, such as material flexibility and attachment design, may affect the precision of tooth movements (Castroflorio et al., 2023). Additionally, patient compliance plays a crucial role in treatment outcomes, as deviations from the prescribed wear schedule can impact the effectiveness of clear aligners in achieving planned movements (Karras et al., 2020). Moreover, the complexity of orthodontic cases, particularly those requiring vertical movements, poses challenges in accurately predicting tooth movements with clear aligners (Khosravi et al., 2016). Factors such as the severity of malocclusion, skeletal discrepancies, and individual patient characteristics can influence treatment outcomes and contribute to discrepancies between planned and actual movements. Furthermore, variations in treatment protocols, including the frequency of aligner changes and the use of auxiliary techniques, can impact the accuracy of tooth movements with clear aligners (Palone et al., 2022).

To enhance the treatment outcome of vertical movements with clear aligners, several strategies can be employed. Firstly, optimising attachment design and placement can improve the control and precision of tooth movements (Karras et al., 2020). Additionally, overcorrecting tooth movements and incorporating staging techniques can help compensate for potential discrepancies between planned and actual movements (Khosravi et al., 2017).

Krieger et al. (2012) stated that vertical plane movements, particularly pertaining to the overbite parameter, exhibited more pronounced deviations compared to other parameters. These deviations averaged at -0.71 mm, with individual deviations ranging from a minimum of -2.25 mm to a maximum of 1.00 mm. Even after adjustment and rigorous testing for equivalence, the overbite outcomes surpassed the defined confidence interval, unlike all other investigated parameters. This underscores the persistent challenge associated with achieving vertical tooth movements using the Invisalign technique, in contrast to transverse or sagittal tooth movements. Hence, they recommend employing bilateral horizontal right-angled attachments in the premolar region or using vertical elastics for patients requiring extensive vertical tooth movements to enhance aligner retention. This suggests that during Clin Check planning, orthodontists may need to incorporate additional case refinements or consider overcorrecting the overbite. This could potentially lead to longer treatment durations or a higher number of aligners. Therefore, orthodontists must carefully assess vertical tooth movements due to their tendency for less accurate outcomes.

Furthermore, clinicians should consider individual patient factors, such as the severity of malocclusion and skeletal discrepancies, when planning treatment with clear aligners (Haouili et al., 2020). Patient education and reinforcement of compliance are also essential to ensure consistent wear of aligners and maximise treatment effectiveness (Castroflorio et al., 2023). Overall, by employing a comprehensive treatment approach that addresses patient-specific needs and incorporates advanced planning techniques, clinicians can improve the predictability and accuracy of vertical movements with clear aligners.

4.4 Predictability of tipping

The efficacy of clear aligners in achieving predictable tooth movements, particularly in terms of bucco-lingual and mesio-distal movements, has been a subject of extensive research in orthodontics. The findings from various studies shed light on the potential of clear aligners to induce desired tooth movements and improve treatment outcomes.

Kravitz et al. (2009) reported that the mean accuracy of mesiodistal tip correction with Invisalign was found to be 40.5%. Their study also revealed variations in accuracy across different teeth. The highest accuracy in mesiodistal movement was observed in the maxillary (43.1%) and mandibular (48.6%) lateral incisors. On the other hand, the maxillary (35.5%) and mandibular (26.9%) canines, as well as the maxillary central incisors (38.6%), exhibited the lowest accuracy. These findings suggest that teeth with larger roots, such as canines and central incisors, might encounter greater difficulty in achieving mesiodistal movement with Invisalign. The study findings also indicate that lingual crown tip corrections were significantly more accurate (53.1%) compared to labial crown tip corrections (37.6%), especially for the maxillary incisors. This insight could prove especially beneficial in treating patients diagnosed with Class II Division 2 malocclusion. It suggests that while it may be advantageous to intentionally overcorrect the forward positioning of the maxillary central incisors, a similar adjustment might not be necessary for the backward positioning of flared lateral incisors.

Ravera et al. (2016) concluded in their study that aligner therapy can distalize the first molar (2.25 mm) in association with composite attachments and Class II elastics without significant tipping or vertical movement of the crown, and no change to the facial height was observed. The amount of distal movement of maxillary molars obtained in this study was comparable to those obtained in Simon et al. (2014).

Research indicates that clear aligners can indeed achieve significant B-L and M-D movements, as demonstrated by studies such as those by Lione et al. (2022) and Morales-Burruezo et al. (2020). These studies show statistically significant changes in tooth inclination and position following clear aligner treatment, particularly in molars. Additionally, subgroup analyses suggest that the presence of cross-bites may influence the magnitude of these changes, highlighting the importance of patient-specific considerations in treatment planning.

The findings from Houili et al. (2020) are insightful regarding the accuracy of different tooth movements with clear aligners. They suggested that the most accurate tooth movement was the bucco-lingual crown tip, with an accuracy of 56%. This observation aligns with the physical properties of aligner materials, which primarily flex in a bucco-lingual direction, making it easier to achieve this type of movement.

However, despite the demonstrated efficacy of clear aligners in inducing tooth movements, the treatment outcomes may not always align perfectly with digital planning. Various factors contribute to this discrepancy in accuracy. One major factor is the influence of attachments, as highlighted by Simon et al. (2014) and Castroflorio et al. (2023). Optimised attachments have been shown to enhance the accuracy of tooth movement compared to conventional attachments or no attachments. Additionally, aligner change frequency and tooth inclination/angulation play significant roles in movement accuracy, as evidenced by studies such as those by Castroflorio et al. (2023) and Palone et al. (2022). These findings underscore the importance of attachment optimisation, aligner change protocols, and personalised treatment planning to improve treatment outcomes.

In reviewing the literature concerning tooth movements facilitated by clear aligners, it is essential to acknowledge potential biases that may influence the interpretation of results. One potential bias lies in the selection of studies included in the analysis. Studies with positive outcomes may be more likely to be published or cited, leading to an overestimation of the efficacy of clear aligners in achieving desired tooth movements. Additionally, studies funded by manufacturers of clear aligner systems may introduce bias due to conflicts of interest.

Moreover, the methods used to assess treatment outcomes may vary between studies, leading to inconsistencies in the reported results. For example, differences in the definition of movement accuracy or the criteria used to evaluate treatment success may impact the comparability of findings across studies. Furthermore, the expertise and experience of orthodontists involved in treatment planning and execution may influence the success rates of clear aligner therapy, introducing another potential source of bias.

To mitigate these biases, future research should strive for transparency in reporting methodologies and outcomes. Standardisation of assessment protocols and the adoption of objective measures for evaluating treatment success can enhance the reliability and validity of study findings. Additionally, independent funding and peer review processes can help minimise conflicts of interest and ensure the integrity of research in this field.

Conclusions

In conclusion, this review has explored the effectiveness of clear aligners in orthodontic tooth movements, addressing three key questions: the predictability of movements, reasons for discrepancies between digital planning and actual outcomes, and strategies for improving treatment results in rotation, vertical movement, expansion, and mesio-distal and bucco-lingual movements.

Clear aligners can achieve significant tooth movements, but predictability varies. Studies report an average accuracy range of 41% to 73%, influenced by factors such as movement complexity, magnitude, and tooth characteristics. For rotations, especially those exceeding 15 degrees, aligners show reduced accuracy. Vertical movements, particularly incisor intrusion and molar extrusion, also present challenges, with lower predictability compared to other movements. However, aligners are generally effective for M-D and B-L movements, and dental arch expansion, though the latter often involves tipping rather than bodily movement.

Our analysis indicates that discrepancies do exist between ClinCheck simulations and real-life outcomes. These differences vary depending on the type of tooth movement being assessed. For rotational movements, the precision of ClinCheck often diverges from clinical reality, with actual rotations frequently falling short of the planned values. Similarly, vertical movements exhibit variations, with some teeth not achieving the projected extrusion or intrusion, thus affecting the overall vertical alignment. Expansion, another critical aspect of orthodontic treatment, also shows a notable difference between ClinCheck projections and actual results. While ClinCheck provides a detailed plan for expanding the dental arches, the achieved expansion may be less pronounced than expected, potentially necessitating adjustments in the treatment plan. In terms of mesio-distal and bucco-lingual movements, our findings reveal that while ClinCheck can predict the general direction and extent of movement, the exact positioning of teeth often varies. These discrepancies highlight the challenges in achieving precise tooth alignment as initially planned by the digital simulation.

To enhance clear aligner treatment outcomes, several strategies can be employed. Firstly, optimising attachment designs can improve movement accuracy. Secondly, frequent aligner changes can maintain continuous force application and minimise aligner deformation, improving predictability.

In summary, while clear aligners offer a promising alternative to traditional braces, achieving perfect predictability in all planned movements remains challenging. By refining attachment designs, optimising treatment protocols, and enhancing patient compliance, clinicians can improve the predictability and precision of tooth movements with clear aligners. Continued research and technological advancements will further enhance treatment outcomes, ultimately leading to better results for patients with various malocclusions.

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Ethical approval

No ethical approval was required for this study as it did not involve human participants, animal subjects, or sensitive data. This study falls under the category of data collection without participant identification.

Consent for publication

Not applicable.

Authors' contributions

The author(s) declare that all the criteria for authorship designated by the International Committee of Medical Journal Editors have been met. More specifically, these are: (a) Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND (b) Drafting the work or revising it critically for important intellectual content; AND (c) Final approval of the version to be published; AND (d) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Competing interests

The author(s) declare that there are no competing interests related to this work.

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