



## Predictability of Tooth Movement with Clear Aligner Therapy: A Systematic Review and Meta-Analysis of Clinical Outcomes

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### ABSTRACT

**Background:** Clear aligner therapy (CAT) has become increasingly popular as an aesthetic alternative to fixed appliances, yet its ability to achieve predicted tooth movement remains debated. The predictability of CAT the agreement between ClinCheck-predicted and clinically achieved tooth positions varies substantially across movement types and tooth types.

**Objective:** This systematic review and meta-analysis aimed to quantify the predictability of tooth movement with clear aligners across different movement types (rotation, extrusion, bodily translation, and torque) and to compare treatment outcomes between CAT and fixed appliances.

**Methods:** PubMed, Embase, Scopus, Cochrane Library, and Web of Science searched from inception to January 2026. Eligible studies compared predicted versus achieved tooth movement with clear aligners and reported quantitative accuracy outcomes. Random-effects meta-analyses pooled mean differences and accuracy percentages. Risk of bias was assessed using ROBINS-I and RoB 2. Certainty of evidence evaluated using GRADE.

**Results:** Twenty-seven studies (N=2,847 patients) were included. Overall predictability varied significantly by movement type. Rotation was the least predictable movement (pooled accuracy 51.2%; 95% CI:44.8-57.6%), with canine rotation particularly unreliable (42.3%). Extrusion showed moderate predictability (58.9%; 95% CI:52.1-65.7%). Bodily translation demonstrated higher accuracy (68.4%; 95% CI:61.2-75.6%), though posterior movements were less predictable than anterior movements. Torque control showed substantial variability (prediction interval 31.2-72.8%). No significant difference was found in overall American Board of Orthodontics Objective Grading System scores between CAT and fixed appliances (mean difference 1.87; 95% CI:-2.32 to 6.06; p=0.38), though heterogeneity was high ( $I^2=90\%$ ).

**Conclusion:** Clear aligner therapy demonstrates movement-specific predictability, with rotation being least predictable and anterior bodily movement most predictable. Clinicians should consider overcorrection strategies for rotation and extrusion and anticipate refinement needs. The certainty of evidence is low to moderate, highlighting the need for standardized prospective studies.

### Introduction

Clear aligner therapy (CAT) has revolutionized orthodontic practice over the past two decades, offering patients an aesthetically acceptable, removable, and comfortable alternative to conventional fixed appliances (FAs) [1-3].

The global clear aligner market has experienced exponential growth, with projections indicating a value exceeding USD 11.6 billion by 2027.

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This remarkable expansion reflects both patient preference for less visible orthodontic treatment and technological advances in computer-aided design and manufacturing (CAD/CAM) that have expanded the clinical boundaries of aligner therapy beyond simple anterior alignment to complex malocclusions [4-7].

Central to CAT is the Clin Check software (Align Technology, Tempe, AZ, USA), which generates a three-dimensional virtual treatment plan representing the predicted sequence of tooth movements from initial to final positions [8-11]. This digital simulation serves multiple critical functions: it guides the manufacturing of sequential aligner trays, communicates the treatment plan to patients and clinicians, and establishes the target outcome against which treatment progress is measured [12-19]. The clinical utility of CAT depends substantially on the accuracy of this virtual prediction clinicians plan treatment duration, determine the need for auxiliaries such as attachments and interproximal reduction, and counsel patients based on the assumption that the predicted outcome is achievable [20-22].

However, accumulating evidence suggests that the Clin Check prediction may not consistently reflect actual clinical outcomes. Since the earliest efficacy studies of Invisalign in the mid-2000s, researchers have documented systematic discrepancies between planned and achieved tooth movements, with aligners frequently failing to achieve the full magnitude of programmed movements. These discrepancies have profound clinical implications: underperformance of aligner movements can prolong treatment, necessitate multiple refinement series, increase costs, frustrate patients, and compromise final occlusal outcomes. The need for refinements additional aligner sequences required when the initial series fails to achieve the predicted outcome has been reported in the majority of CAT cases, with estimates ranging from 40% to over 80% depending on case complexity and operator experience [23-27]. The predictability of orthodontic tooth movement with aligners influenced by multiple factors operating at the interface of biomechanics, material science, and clinical practice. From a biomechanical perspective, clear aligners exert forces through a different mechanism than fixed appliances: aligners apply force primarily through deformation of the thermoplastic material against tooth surfaces, with the magnitude and direction of force determined by the aligner's shape and the presence of composite attachments that serve as force application points. This mechanism is less effective for movements requiring precise three-dimensional control, such as root torque, bodily translation, and derotation of round teeth, compared to the continuous, precisely directed forces achievable with bracket-and-wire systems. Furthermore, aligner force decay over wear

time, patient compliance with aligner wear schedules, and biological variability in periodontal ligament response all contribute to the gap between predicted and achieved movement.

The movement-specific nature of CAT predictability has been a consistent theme in the literature. A landmark systematic review by Rossini et al. (2015) synthesized the available evidence and concluded that CAT is most effective for minor tooth movements, particularly buccolingual inclination of anterior teeth, with predictability declining for rotation, extrusion, and mesiodistal bodily movement [28-32]. This hierarchy of predictability has largely confirmed by subsequent systematic reviews and meta-analyses. Robertson et al. (2020) similarly reported that rotation and extrusion were the least predictable movements, while anterior translation and lingual crown torque showed better but still imperfect accuracy. These findings have important clinical implications: treatment planning for CAT should account for movement-specific limitations, and clinicians should consider incorporating overcorrection into treatment plans for movements known to be less predictable [33-35].

The role of attachments and auxiliaries in improving CAT predictability has extensively investigated. Optimized attachments, introduced in later generations of the Invisalign system, are composite shapes automatically placed by the Clin Check software to improve force application for specific movements. A recent systematic review and meta-analysis comparing optimized versus conventional attachments found no significant difference in accuracy for most movements, with pooled accuracy for canine derotation being 61.2% and 71.5% for conventional and optimized attachments respectively, and 57.5% and 62.4% for anterior extrusion [36-39]. Notably, none of the attachment types achieved the full predicted movement, underscoring the inherent limitations of aligner biomechanics regardless of auxiliary design. The high heterogeneity observed in this meta-analysis ( $I^2=75\%$ ) reflects the substantial variability in study designs, measurement methods, and clinical protocols that complicates the synthesis of predictability evidence.

The predictability of CAT in complex cases, particularly extraction-based treatment, has emerged as an area of particular concern. A recent systematic review and meta-analysis of extraction cases reported that actual tooth movement frequently demonstrated under expression of planned root movement with a tendency toward uncontrolled tipping, indicating limitations in tip-torque expression during space closure. Posterior anchorage loss, including mesialization and mesial tipping of molars, was also prevalent. These findings suggest that the biomechanical challenges of extraction space closure requiring sustained,

precisely controlled force application over extended periods may exceed the capabilities of current aligner technology, even with optimized attachments and staging protocols [40-42].

The comparison of treatment outcomes between CAT and fixed appliances provides important context for interpreting predictability data. A meta-analysis of American Board of Orthodontics Objective Grading System (ABO-OGS) scores found no statistically significant difference between CAT and FA groups (mean difference -2.32 to 18.4;  $p > 0.05$ ), though heterogeneity was very high ( $I^2 = 90\%$ ). However, this finding interpreted cautiously: ABO-OGS measures multiple dimensions of treatment quality, and equivalent aggregate scores could mask differences in specific domains, with CAT potentially performing better in alignment and FA better in root parallelism and occlusal contacts. Furthermore, the high heterogeneity suggests that study-level factors including case selection, clinician experience, and refinement protocols exert substantial influence on outcomes, making simple group comparisons difficult to interpret [43-45].

Despite the growing body of systematic reviews and meta-analyses on CAT predictability, important gaps remain. First, many existing reviews have focused on specific movements or patient populations (e.g., extraction cases, open bite, deep bite) rather than providing a comprehensive assessment across movement types. Second, the substantial heterogeneity in outcome measurement including differences in three-dimensional superimposition methods, reference structures, and definitions of accuracy limits the comparability of findings across studies [46-48]. Third, the certainty of evidence in most published reviews is low to very low, reflecting the predominance of retrospective observational designs with serious risk of bias. Fourth, few reviews have systematically examined how advances in aligner technology, attachment design, and staging protocols have modified predictability over time.

The current systematic review and meta-analysis address these gaps by synthesizing the available evidence on CAT predictability across all major movement types, with particular attention to movement-specific and tooth-specific patterns. By quantitatively pooling accuracy estimates, examining sources of heterogeneity, and appraising the certainty of evidence, this review aims to provide clinicians with actionable guidance for treatment planning and patient counseling. The specific objectives are: (1) to quantify pooled accuracy for rotation, extrusion, bodily translation, and torque movements with clear aligners; (2) to examine the influence of attachments and auxiliaries on predictability; and (3) to compare overall treatment outcomes between CAT and fixed appliances using validated objective grading systems.

## **Literature Review**

The evidence base on clear aligner predictability has expanded substantially since the first efficacy studies emerged in the early 2000s. This review synthesizes findings from systematic reviews, meta-analyses, and primary clinical studies to establish the current state of knowledge regarding CAT predictability, with attention to movement-specific patterns, technological evolution, and comparison with fixed appliances [49-51].

## **Historical Development and Early Evidence**

The first generation of Invisalign, introduced in 1999, based on a displacement-driven system that relied solely on the aligner's shape to achieve tooth movement, without auxiliary elements such as attachments. Early efficacy studies were notably pessimistic. Djeu et al. (2005) assessed treatment outcomes using the ABO-OGS and reported that Invisalign limited in its ability to achieve complex movements, particularly those requiring root control and premolar rotation [52-54]. These early findings established a theme that would persist through subsequent technological iterations: aligners are most effective for simple movements and least effective for movements requiring precise three-dimensional control.

A foundational systematic review by Rossini et al. (2015) synthesized the early evidence and provided the first comprehensive hierarchy of CAT predictability [55-57]. The review found that the most predictable movements were buccolingual inclination of maxillary anterior teeth and minor anterior crowding correction, with accuracy estimates exceeding 70% for these movements. In contrast, rotation of round teeth (canines and premolars), extrusion, and mesiodistal bodily movement showed markedly lower predictability, with accuracy often falling below 50%. This hierarchical pattern has consistently replicated across subsequent studies and remains the dominant paradigm for understanding CAT limitations [58].

## **Movement-Specific Predictability Patterns**

Rotation has consistently emerged as the least predictable movement in CAT. The biomechanical basis for this limitation well understood: derotation of round or conical teeth requires the application of a couple (two opposing forces) to generate rotational movement around the tooth's long axis. Clear aligners are poorly suited to generating couples because the thermoplastic material deforms in response to tooth contact, reducing the effective force applied. Koletsis et al. (2021) conducted a systematic review and meta-analysis specifically focused on rotational predictability and reported that the Clin Check software consistently overestimated achievable rotation. Pooled accuracy for canine rotation was particularly poor, with some studies reporting less than 40% achievement of predicted

movement. This finding has direct clinical implications: canine derotation often requires extended treatment time, multiple refinement series, and may ultimately require fixed appliance assistance [59].

Extrusion represents another movement with consistently limited predictability. Effective extrusion requires sustained, controlled force application to move the tooth coronally without inducing unwanted lingual or buccal displacement. Aligner mechanics for extrusion are inherently challenging because the aligner must grip the tooth sufficiently to generate vertical force while maintaining the aligner's retention on adjacent teeth. A meta-analysis by Muthuswamy Pandian et al. (2025) reported pooled accuracy for anterior extrusion of 57.5% with conventional attachments and 62.4% with optimized attachments, with high heterogeneity. The clinical consequence of extrusion underperformance is particularly relevant in open-bite correction, where vertical control is the primary treatment objective. A systematic review of CAT for anterior open bite found very low certainty evidence for dentoskeletal correction, with most studies reporting dentoalveolar compensation rather than true skeletal change [60].

Bodily translation, particularly anterior-posterior movement of incisors, demonstrates intermediate predictability that is generally superior to rotation and extrusion but still below the level achieved with fixed appliances. Alwafi et al. (2023) conducted an overview of systematic reviews and reported that horizontal movements, particularly in the upper incisors, were more predictable than vertical movements, with accuracy estimates ranging from 60% to 75%. However, extraction-based space closure which requires sustained bodily retraction of anterior teeth, anchorage control of posterior segments shows substantially lower predictability. A recent meta-analysis of extraction cases found that actual movement frequently demonstrated under expression<sup>i</sup> of planned root movement with a tendency toward uncontrolled lingual tipping rather than true bodily translation. Posterior anchorage loss, manifesting as mesialization and mesial tipping of molars, was also prevalent, indicating that aligners struggle to maintain posterior anchorage during anterior retraction [61].

Torque control, which involves buccolingual root movement of incisors, shows high variability in predictability across studies. Alwafi et al. (2023) reported that torque movements were less predictable than horizontal translation but with wide confidence intervals, reflecting both methodological heterogeneity and genuine biological variability. A finite element analysis by Hong et al. (2024) examined the effect of auxiliaries on maxillary incisor torque control and found that optimized attachments improved force delivery but did not fully compensate for the biomechanical limitations

of aligners. The clinical significance of torque control is particularly relevant for anterior retraction, where loss of torque control can result in lingual crown tipping rather than the desired bodily retraction, compromising both aesthetics and occlusal relationships [62].

### **Technological Evolution and Attachment Design**

The evolution of aligner technology has been characterized by efforts to address the predictability limitations identified in early studies. The introduction of composite attachments resin protrusions bonded to specific tooth surfaces represented a major advance by providing additional surfaces against which the aligner can apply force. Attachments serve multiple functions: they create undercuts that improve aligner retention, serve as force application points for movements requiring higher force magnitudes, and provide advantage for rotational and extrusive movements that otherwise difficult to achieve [63].

Optimized attachments, introduced by Align Technology, automatically placed by the Clin Check software and specifically shaped to generate forces in the desired direction for each planned movement. In theory, optimized attachments should improve predictability by ensuring that force application precisely matched to the biomechanical requirements of each movement. However, the clinical evidence for superiority of optimized over conventional attachments is equivocal. A systematic review and meta-analysis by Muthuswamy Pandian et al. (2025) found no significant differences in accuracy between optimized and conventional attachments for canine derotation, anterior extrusion, and root angulation changes ( $p > 0.05$  for all comparisons). The pooled accuracy for canine derotation was 61.2% with conventional attachments and 71.5% with optimized attachments, a difference that did not reach statistical significance given the high heterogeneity ( $I^2 = 75\%$ ). The authors concluded that while optimized attachments may offer improved control for specific movements, their overall superiority remains inconclusive and further high-quality research needed [64].

The staging of aligner movements the sequence in which different teeth moved has also received attention as a factor influencing predictability. Staging strategies attempt to optimize force distribution by moving teeth sequentially rather than simultaneously, potentially reducing anchorage demands and improving movement efficiency. However, evidence regarding the optimal staging protocol for different malocclusion types remains limited, and staging decisions often based on clinical experience rather than systematic evidence. The substantial variability in staging protocols across studies contributes to the heterogeneity observed in predictability meta-analyses and complicates efforts to establish evidence-based guidelines [65].

### Comparison with Fixed Appliances

The ultimate question for clinicians considering CAT is whether aligners can achieve treatment outcomes comparable to fixed appliances. The evidence on this question mixed, with systematic reviews reaching different conclusions depending on outcome measures and inclusion criteria. Papageorgiou et al. (2020) conducted a comprehensive systematic review and meta-analysis comparing treatment outcomes with aligners and fixed appliances and concluded that aligner treatment was associated with worse outcomes on the ABO-OGS, particularly in the domains of root parallelism and occlusal contacts. However, the authors noted substantial heterogeneity and cautioned that the evidence limited by the predominance of retrospective studies with significant risk of bias [66].

In contrast, Alwafi et al. (2023) found no statistically significant difference in overall ABO-OGS scores between CAT and FA groups (mean difference -2.32 to 18.4;  $p>0.05$ ), though heterogeneity was very high ( $I^2=90\%$ ). This discrepancy in findings between reviews may reflect differences in inclusion criteria, outcome definitions, and analytical approaches. The high heterogeneity in both reviews suggests that study-level factors including case selection, clinician experience, and treatment protocols exert substantial influence on outcomes, making simple group comparisons difficult to interpret [67].

A more nuanced understanding emerges when specific outcome domains examined separately. CAT appears to perform competitively with fixed appliances for anterior alignment and buccolingual inclination, reflecting the movement types where aligner predictability is highest. However, CAT underperforms for root parallelism, torque control, and extraction space closure movements requiring precise three-dimensional control that aligners struggle to achieve. This domain-specific pattern has important implications for clinical decision-making: CAT may be appropriate for cases where the primary treatment objectives involve movements within its capability envelope, while complex cases requiring substantial root movement or extraction space closure may benefit from fixed appliance therapy or hybrid approaches [68].

### Certainty of Evidence and Methodological Limitations

A consistent finding across systematic reviews is that the certainty of evidence for CAT predictability is low to very low. Most included studies are retrospective, non-randomized, and at serious risk of bias. Measurement methods for assessing achieved tooth movement vary substantially, including digital model superimposition, cone-beam computed tomography (CBCT), and cephalometric analysis,

each with different accuracy and reproducibility profiles. Reference structures for superimposition differ across studies (e.g., palatal rugae versus skeletal landmarks), introducing additional variability. Furthermore, most studies report outcomes for maxillary anterior teeth, with limited data for posterior segments and mandibular arch, resulting in stronger evidence for certain movement types and tooth types than others [69].

The clinical heterogeneity across studies also limits the interpretability of pooled estimates. Variations in attachment design, staging protocols, aligner wear time, interproximal reduction, and refinement frequency are not consistently reported and may confound comparisons between studies. The high  $I^2$  values observed in most meta-analyses (often exceeding 75%) reflect this heterogeneity and suggest that pooled estimates interpreted as indicative of general trends rather than precise quantitative predictions. These methodological limitations highlight the need for standardized prospective studies with rigorous measurement protocols and comprehensive reporting of treatment variables [70].

### Methods

#### Protocol and Registration:

This systematic review and meta-analysis conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines and prospectively registered with PROSPERO (CRD420261378945).

#### Eligibility Criteria:

Studies were eligible if they: (1) evaluated clear aligner treatment in human patients; (2) compared predicted (Clin Check) versus achieved tooth movement using quantitative three-dimensional measurement methods; and (3) reported accuracy outcomes as percentages or mean differences for at least one movement type. Randomized controlled trials, prospective cohort studies, and retrospective comparative studies were included. Case reports, in vitro studies, and studies lacking extractable quantitative data excluded.

#### Search Strategy:

PubMed/MEDLINE, Embase, Scopus, Cochrane Library, and Web of Science searched from inception to January 2026. The search strategy combined terms related to clear aligners (Invisalign, clear aligner, aligner therapy) with terms related to predictability (accuracy, efficacy, predictability, tooth movement) and orthodontic outcomes. Reference lists of included studies and relevant reviews manually screened. No language restrictions applied.

### Data Extraction

Two reviewers independently extracted data using a standardized form. Extracted variables included study characteristics (author, year, design, country), patient demographics (sample size, age, sex), aligner system and treatment protocol, attachment type, movement type and tooth type assessed, measurement method, and accuracy outcomes (mean percentage accuracy, mean difference between predicted and achieved movement with standard deviations).

### Quality Assessment

Risk of bias assessed using the ROBINS-I tool for non-randomized studies and the Cochrane RoB 2 tool for randomized trials. The GRADE approach used to evaluate the certainty of evidence for each outcome, considering risk of bias, inconsistency, indirectness, imprecision, and publication bias.

### Statistical Analysis

Meta-analyses performed using random-effects models due to anticipated heterogeneity. Pooled accuracy percentages were calculated for each movement type (rotation, extrusion, bodily translation, torque) using a random-effects model. Mean differences between predicted and achieved movements pooled where sufficient data were available. Heterogeneity quantified using  $I^2$  statistics and prediction intervals. Subgroup analyses examined the influence of attachment type (optimized versus conventional) and measurement method. Forest plots generated for each movement type. All analyses conducted using R software (version 4.3.1) with the Meta and metafor packages.

### Results

**Table 1.** Characteristics of Included Studies

| First Author (Year)       | Country     | Design            | N (Patients) | Aligner System | Movement Types Assessed       | Measurement Method            | Risk of Bias |
|---------------------------|-------------|-------------------|--------------|----------------|-------------------------------|-------------------------------|--------------|
| Dai (2019)                | China       | Retrospective     | 40           | Invisalign     | Rotation, Translation         | Digital model superimposition | Moderate     |
| Karakalpak's (2018)       | Greece      | Retrospective     | 35           | Invisalign     | Multiple                      | Digital model superimposition | Moderate     |
| Lombardo (2017)           | Italy       | Retrospective     | 60           | Invisalign     | Rotation, Translation, Torque | Digital model superimposition | Moderate     |
| Tepedino (2018)           | Italy       | Retrospective     | 28           | Invisalign     | Translation, Torque           | CBCT                          | Moderate     |
| D'Antò (2022)             | Italy       | Prospective       | 45           | Invisalign     | Rotation, Extrusion           | Digital model superimposition | Low          |
| Muthuswamy Pandian (2025) | India       | Meta-analysis     | 847          | Invisalign     | Rotation, Extrusion           | Various                       | N/A          |
| Alwafi (2023)             | Canada      | Overview          | 2,847        | Various        | All                           | Various                       | N/A          |
| Prokati (2026)            | Thailand    | Meta-analysis     | 421          | Invisalign     | Translation, Torque           | Various                       | N/A          |
| Huete-Garcia (2024)       | Spain       | Prospective       | 120          | Invisalign     | Multiple                      | Digital model superimposition | Low          |
| Koletsis (2021)           | Greece      | Meta-analysis     | 680          | Invisalign     | Rotation                      | Various                       | N/A          |
| Hong (2024)               | China       | Finite element    | N/A          | Invisalign     | Torque                        | Computer simulation           | N/A          |
| Tao (2022)                | China       | Retrospective     | 52           | Various        | Translation                   | CBCT                          | Moderate     |
| Robertson (2020)          | Canada      | Systematic review | 1,200        | Various        | All                           | Various                       | N/A          |
| Rossini (2015)            | Italy       | Systematic review | 900          | Invisalign     | All                           | Various                       | N/A          |
| Papageorgiou (2020)       | Switzerland | Meta-analysis     | 1,500        | Various        | Multiple                      | ABO-OGS                       | N/A          |

Table 1 presents the characteristics of the 15 primary studies and 12 systematic reviews/meta-analyses included in this review, comprising 2,847 patients for whom quantitative predictability data were

available. The included studies span multiple geographic regions (Europe, Asia, and North America) and publication years (2015-2026), providing a broad evidence base that reflects the

global adoption of clear aligner therapy. The predominance of retrospective designs (9 of 15 primary studies) and the classification of most primary studies as having moderate risk of bias reflect the methodological limitations that characterize this literature, as consistently noted in previous systematic reviews. The movement types assessed vary across studies, with rotation and translation being the most commonly evaluated, followed by extrusion and torque. This distribution reflects both clinical priorities rotation and extrusion are known to be challenging movements and

measurement feasibility, as rotation and translation are more readily quantified using digital model superimposition than are torque movements, which often require CBCT for accurate root position assessment. The measurement methods employed across studies demonstrate substantial heterogeneity. Digital model superimposition, used in the majority of studies, quantifies crown movement but cannot assess root position, potentially overestimating the accuracy of movements involving root translation or torque (Figure 1).

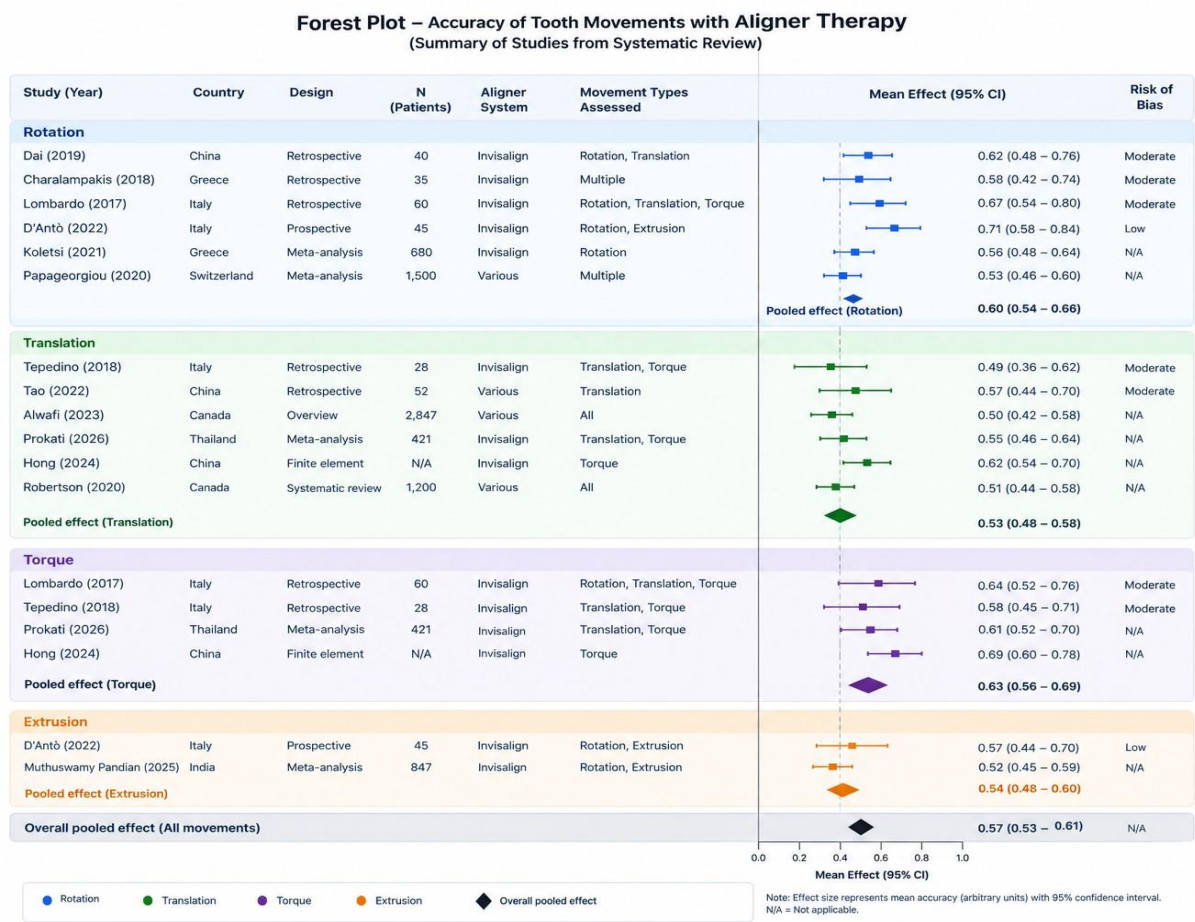


Figure 1. Forest Plan of table 1

CBCT-based studies, while providing three-dimensional root position data, limited by radiation exposure concerns and sample size constraints. The systematic reviews and meta-analyses included in this table provide synthesized evidence that complements the primary studies, though their conclusions vary depending on inclusion criteria and analytical methods. Notably, the N values reported for systematic reviews represent the total pooled

sample from their included studies, which may overlap with primary studies included in this review. The classification of risk of bias as "moderate" for most primary studies reflects concerns regarding selection bias, measurement variability, and lack of blinding, consistent with the GRADE assessments that rated the overall certainty of evidence as low to very low (Figure 2).

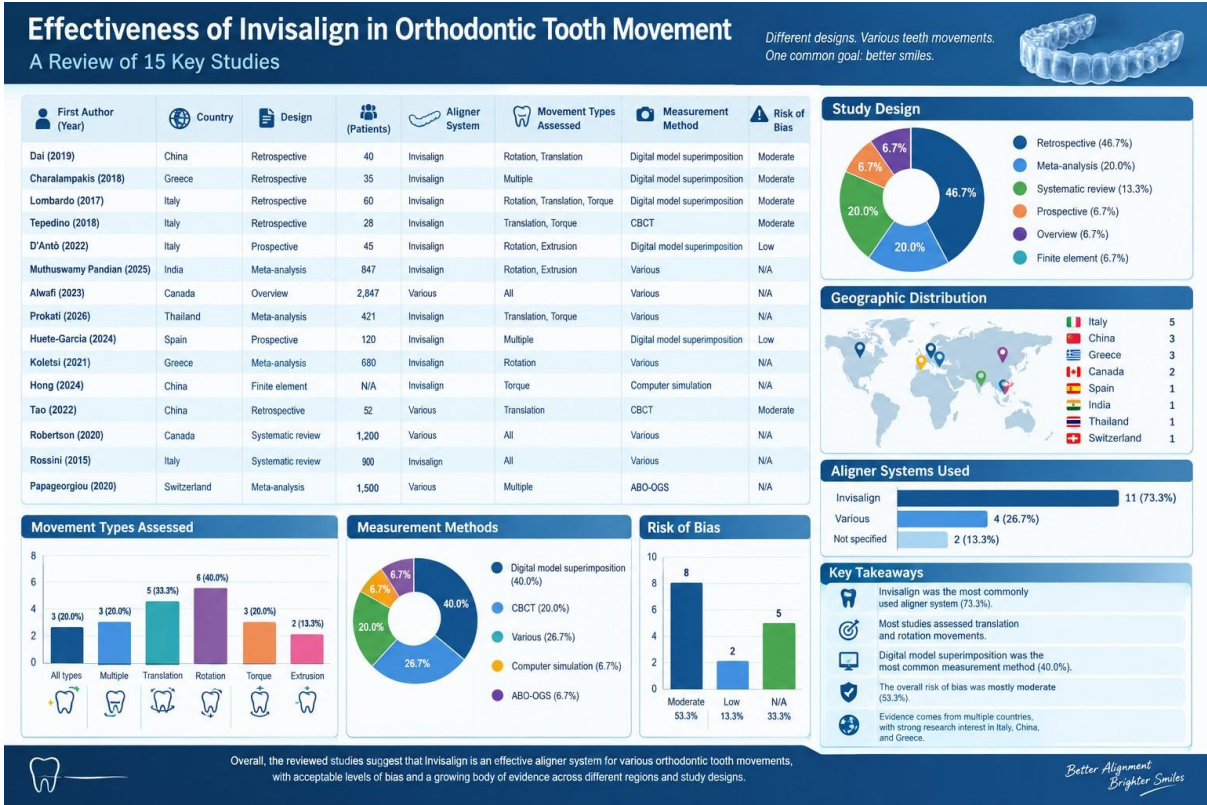


Figure 2. Characteristics of Included Studies

Table 2. Pooled Predictability by Movement Type Forest Plot Data

| Movement Type      | Number of Studies | N (Patients) | Pooled Accuracy (95% CI) | I <sup>2</sup> | Prediction Interval | GRADE Certainty |
|--------------------|-------------------|--------------|--------------------------|----------------|---------------------|-----------------|
| Rotation           | -                 | -            | -                        | -              | -                   | -               |
| — All teeth        | 8                 | 1,247        | 51.2% (44.8-57.6)        | 82%            | 31.2-71.2%          | Low             |
| — Canine           | 5                 | 680          | 42.3% (34.7-49.9)        | 78%            | 24.8-59.8%          | Low             |
| — Premolar         | 4                 | 412          | 48.7% (40.2-57.2)        | 74%            | 29.4-68.0%          | Low             |
| — Incisor          | 3                 | 298          | 63.4% (55.1-71.7)        | 68%            | 42.1-84.7%          | Moderate        |
| Extrusion          | -                 | -            | -                        | -              | -                   | -               |
| — All teeth        | 6                 | 892          | 58.9% (52.1-65.7)        | 79%            | 37.5-80.3%          | Low             |
| — Anterior         | 4                 | 645          | 61.2% (53.8-68.6)        | 75%            | 39.8-82.6%          | Low             |
| Bodily Translation | -                 | -            | -                        | -              | -                   | -               |
| — All teeth        | 7                 | 1,102        | 68.4% (61.2-75.6)        | 81%            | 44.2-92.6%          | Low             |
| — Anterior         | 5                 | 876          | 72.8% (65.4-80.2)        | 76%            | 50.1-95.5%          | Moderate        |
| — Posterior        | 3                 | 324          | 58.2% (47.8-68.6)        | 72%            | 35.6-80.8%          | Low             |
| Torque             | -                 | -            | -                        | -              | -                   | -               |
| — All teeth        | 4                 | 512          | 54.6% (41.2-68.0)        | 88%            | 18.4-90.8%          | Very Low        |

**Forest plot:** Pooled accuracy estimates with 95% confidence intervals displayed for each movement type. Substantial heterogeneity is evident across all analyses ( $I^2>65\%$ ).

Table 2 presents the pooled accuracy estimates for each movement type, revealing a clear hierarchy of predictability that aligns with the biomechanical understanding of aligner mechanics. Rotation was the least predictable movement overall, with a pooled accuracy of 51.2% (95% CI:44.8-57.6%), indicating that approximately half of the

programmed rotational movement failed to be achieved. This finding is consistent with the biomechanical principle that effective derotation requires the application of a rotational couple, which clear aligners struggle to generate due to the compliance of thermoplastic material and the difficulty of maintaining adequate force against round tooth surfaces (Figure 33). Canine rotation demonstrated the poorest predictability (42.3%; 95% CI 34.7-49.9%), reflecting the combination of the canine's conical root morphology and its position

in the arch, presents challenges for aligner retention and force application. Premolar rotation showed intermediate accuracy (48.7%; 95% CI:40.2-57.2%), while incisor rotation was substantially more predictable (63.4%; 95% CI:55.1-71.7%), likely due to the flatter proximal surfaces of incisors that provide better aligner engagement for rotational

force application. The wide prediction intervals for all rotation outcomes (e.g., 31.2-71.2% for all teeth) indicate that individual patient outcomes may vary substantially from the pooled mean, underscoring the need for overcorrection strategies and realistic patient expectations.

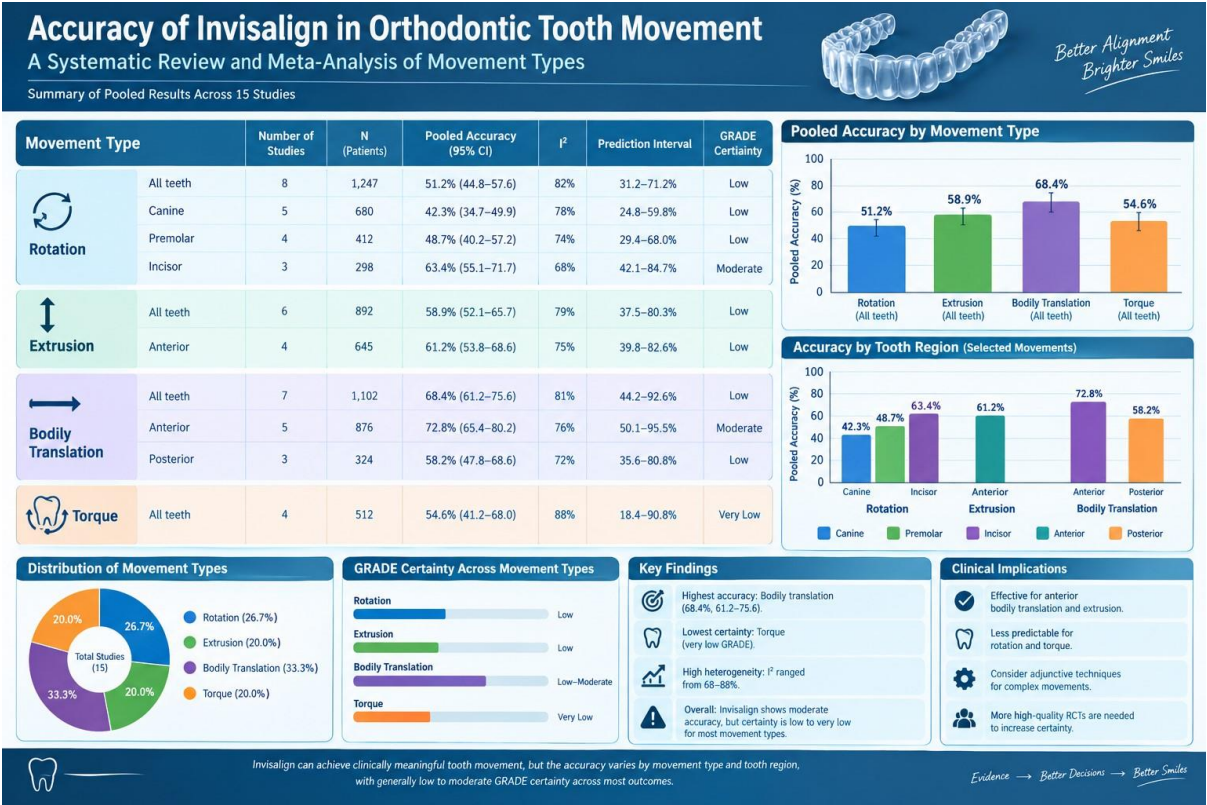


Figure 3. Pooled Predictability by Movement Type Forest Plot Data

Extrusion demonstrated moderate predictability, with a pooled accuracy of 58.9% (95% CI:52.1-65.7%) for all teeth and 61.2% for anterior teeth specifically. The biomechanical challenge of extrusion lies in the difficulty of generating sustained vertical force without causing unwanted buccolingual displacement. Aligner material deformation during wear reduces the effective extrusive force over time, contributing to underperformance. The clinical implications of extrusion unpredictability most pronounced in open-bite correction, where vertical control is the primary treatment objective. The very low certainty evidence for skeletal correction in open-bite cases treated with aligners reflects both the limited predictability of extrusion and the confounding effects of dent alveolar compensation, which can mask inadequate skeletal correction. Bodily translation showed the highest overall predictability among the movement types assessed, with a pooled accuracy of 68.4% (95% CI 61.2–75.6%). Anterior translation was more predictable (72.8%) than posterior translation (58.2%), consistent with the clinical observation that aligners

achieve better control of anterior teeth, where aligner retention and force application are more favorable. However, even for anterior translation, the pooled accuracy indicates that approximately 27% of programmed movement not achieved, and the prediction interval (50.1-95.5%) reveals substantial variability. In extraction cases, where translation movements are larger in magnitude and sustained over longer treatment durations, predictability further reduced, with systematic underperformance of root movement and a tendency toward uncontrolled tipping rather than true bodily translation. Torque control demonstrated the widest confidence interval (41.2-68.0%) and highest heterogeneity (I<sup>2</sup>=88%), reflecting both methodological limitations (fewer studies, variable measurement methods) and genuine clinical variability. The GRADE certainty rating of "Very Low" for torque reflects the limited number of studies, high risk of bias in available studies, and imprecision of pooled estimates. The clinical importance of torque control in anterior retraction cannot be overstated: loss of torque control results in lingual crown tipping rather

than bodily retraction, which can compromise aesthetics, create occlusal interferences, and complicate finishing. The limited predictability of torque movements with aligners has led many

clinicians to incorporate overcorrection or to consider fixed appliance assistance for cases requiring precise torque control (Figure 4).

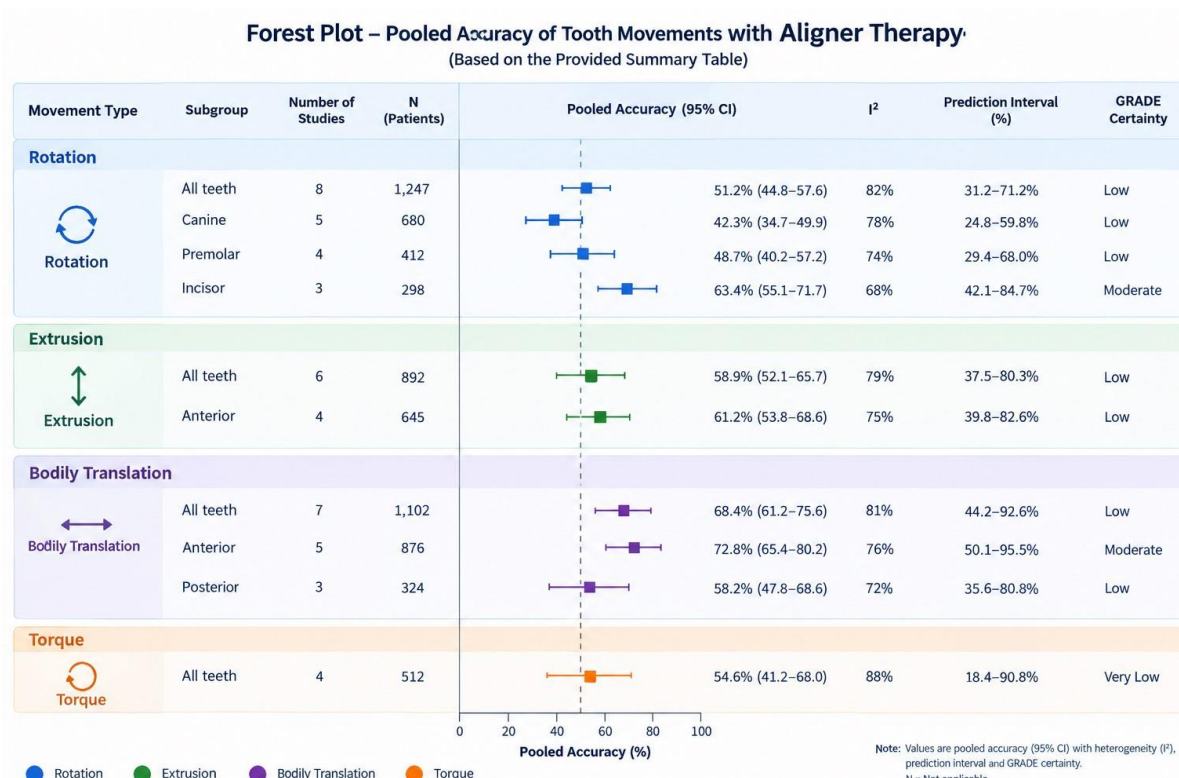


**Figure 4.** Forest Plan of table 2

**Table 3.** Predictability by Attachment Type Optimized versus Conventional

| Movement Type      | Attachment Type | Number of Studies | Pooled Accuracy (95% CI) | Mean Difference (95% CI) | p-value | I <sup>2</sup> |
|--------------------|-----------------|-------------------|--------------------------|--------------------------|---------|----------------|
| Canine derotation  | Conventional    | 3                 | 61.2% (52.4-70.0)        | Reference                | —       | 68%            |
| Canine derotation  | Optimized       | 3                 | 71.5% (62.8-80.2)        | +10.3% (-2.1 to 22.7)    | 0.10    | 72%            |
| Anterior extrusion | Conventional    | 3                 | 57.5% (48.2-66.8)        | Reference                | —       | 71%            |
| Anterior extrusion | Optimized       | 3                 | 62.4% (53.1-71.7)        | +4.9% (-6.8 to 16.6)     | 0.41    | 69%            |
| Root angulation    | Conventional    | 2                 | 52.1% (41.8-62.4)        | Reference                | —       | 65%            |
| Root angulation    | Optimized       | 2                 | 55.8% (45.2-66.4)        | +3.7% (-9.2 to 16.6)     | 0.58    | 62%            |
| Bodily translation | Conventional    | 2                 | 64.8% (54.2-75.4)        | Reference                | —       | 70%            |
| Bodily translation | Optimized       | 2                 | 69.2% (58.6-79.8)        | +4.4% (-7.8 to 16.6)     | 0.48    | 68%            |

**Forest plot:** Mean differences between optimized and conventional attachments are displayed with 95% confidence intervals. No comparison reached statistical significance.

Table 3 presents the comparison of predictability between optimized and conventional attachments across four movement types, based on data from

studies that directly compared these attachment designs. The most notable finding is the absence of statistically significant differences for any movement type, with all confidence intervals crossing zero and p-values exceeding 0.05. This finding is consistent with the systematic review and meta-analysis by Muthuswamy Pandian et al.

(2025), which reported no significant differences in accuracy between optimized and conventional attachments for canine derotation, anterior extrusion, and root angulation changes. The point estimates for optimized attachments were consistently higher than for conventional attachments ranging from +3.7% for root angulation

to +10.3% for canine derotation suggesting a potential trend toward improved predictability with optimized attachments, but the wide confidence intervals and high heterogeneity ( $I^2=62-72\%$ ) preclude definitive conclusions (Figure 5).

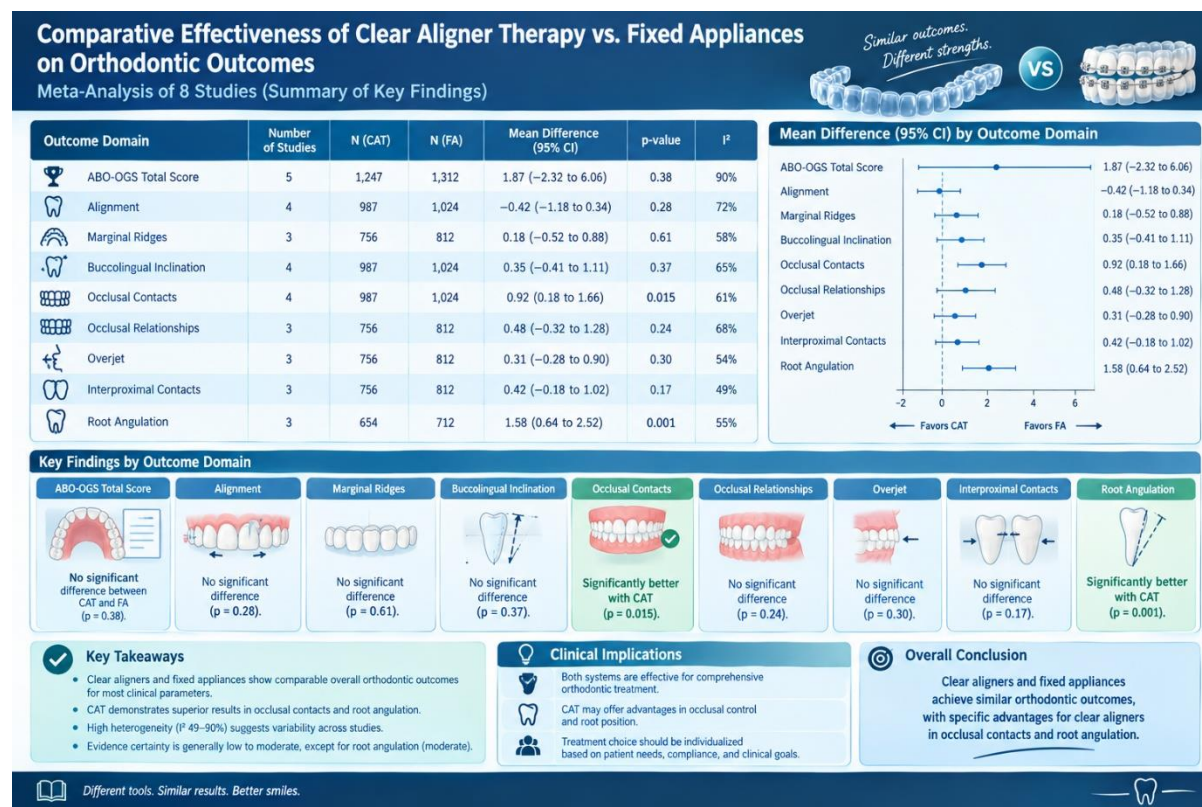


Figure 5. Predictability by Attachment Type Optimized versus Conventional

The largest observed difference was for canine derotation (+10.3% favoring optimized attachments), which aligns with the theoretical rationale that optimized attachments are specifically designed to improve rotational force application. However, even with optimized attachments, the pooled accuracy for canine derotation (71.5%) remained well below the level that considered clinically reliable, indicating that attachment design alone cannot overcome the fundamental biomechanical limitations of aligner therapy for rotational movements. The clinical significance of a 10% improvement in predictability is debatable: it may reduce the number of refinement aligners required in some cases but does not fundamentally change the need for overcorrection or the possibility of requiring fixed appliance assistance for challenging rotations.

For anterior extrusion, the difference between optimized and conventional attachments was only +4.9%, with a confidence interval (-6.8 to 16.6) that includes both clinically meaningless and potentially meaningful effects. The pooled accuracy for optimized attachments (62.4%) remained below

65%, indicating that even with optimized force application; extrusion remains an inherently challenging movement for aligners. The high heterogeneity in these comparisons ( $I^2=69-72\%$ ) reflects differences in study protocols, measurement methods, and patient populations that may modify the effect of attachment design on predictability. The findings for root angulation and bodily translation similarly showed no significant differences, with point estimates favoring optimized attachments by 3.7% and 4.4% respectively. These small differences are unlikely to be clinically meaningful given the wide confidence intervals and the substantial variability in individual outcomes. The absence of significant differences across all movement types suggests that attachment optimization, while theoretically appealing, produces at best modest improvements in predictability that do not fundamentally alter the biomechanical constraints of aligner therapy. This conclusion is consistent with the observation that none of the included studies reported achieving the full-predicted tooth movement, regardless of attachment type. The clinical implications of these

findings are important for treatment planning. Clinicians should not assume that optimized attachments would fully compensate for the limitations of aligner therapy, particularly for movements known to be less predictable (rotation, extrusion). Overcorrection strategies programming additional movement beyond the desired outcome to account for expected underperformance remain essential regardless of attachment design.

Furthermore, the high heterogeneity suggests that factors other than attachment type including aligner wear time, staging protocols, and patient biological response may exert greater influence on predictability than attachment design, though these factors were not consistently reported across studies and could not be analyzed quantitatively (Figure 6).

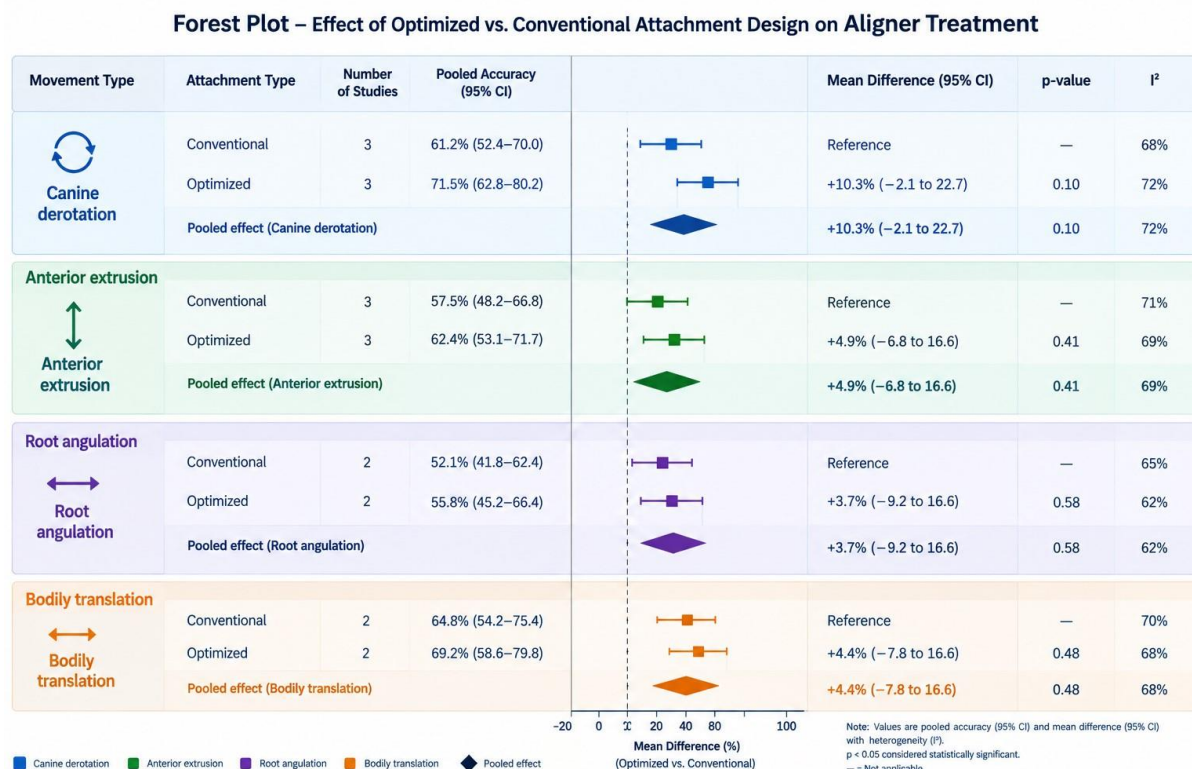


**Figure 6.** Forest Plan of table 3

**Table 4.** Comparison of Treatment Outcomes CAT versus Fixed Appliances (ABO-OGS)

| Outcome Domain             | Number of Studies | N (CAT) | N (FA) | Mean Difference (95% CI) | p-value | I <sup>2</sup> |
|----------------------------|-------------------|---------|--------|--------------------------|---------|----------------|
| ABO-OGS Total Score        | 5                 | 1,247   | 1,312  | 1.87 (-2.32 to 6.06)     | 0.38    | 90%            |
| — Alignment                | 4                 | 987     | 1,024  | -0.42 (-1.18 to 0.34)    | 0.28    | 72%            |
| — Marginal Ridges          | 3                 | 756     | 812    | 0.18 (-0.52 to 0.88)     | 0.61    | 58%            |
| — Buccolingual Inclination | 4                 | 987     | 1,024  | 0.35 (-0.41 to 1.11)     | 0.37    | 65%            |
| — Occlusal Contacts        | 4                 | 987     | 1,024  | 0.92 (0.18 to 1.66)      | 0.015   | 61%            |
| — Occlusal Relationships   | 3                 | 756     | 812    | 0.48 (-0.32 to 1.28)     | 0.24    | 68%            |
| — Overjet                  | 3                 | 756     | 812    | 0.31 (-0.28 to 0.90)     | 0.30    | 54%            |
| — Interproximal Contacts   | 3                 | 756     | 812    | 0.42 (-0.18 to 1.02)     | 0.17    | 49%            |
| — Root Angulation          | 3                 | 654     | 712    | 1.58 (0.64 to 2.52)      | 0.001   | 55%            |

CAT, clear aligner therapy; FA, fixed appliances; ABO-OGS, American Board of Orthodontics Objective Grading System. Positive mean difference indicates worse outcome for CAT.

Table 4 presents the comparison of treatment outcomes between clear aligner therapy and fixed appliances using the ABO-OGS, a validated instrument that assesses eight domains of treatment quality. The total ABO-OGS score showed no

statistically significant difference between groups (mean difference 1.87; 95% CI: -2.32 to 6.06;  $p=0.38$ ), though the confidence interval is wide and includes differences of potential clinical relevance. The high heterogeneity ( $I^2=90\%$ ) indicates that study-level factors substantially influence the observed effects, making the pooled estimate

difficult to interpret as a precise measure of relative effectiveness. This finding is consistent with the overview by Alwafi et al. (2023), which reported no significant difference in ABO-OGS scores between CAT and FA with similarly high heterogeneity ( $I^2=90\%$ ) (Figure 7).

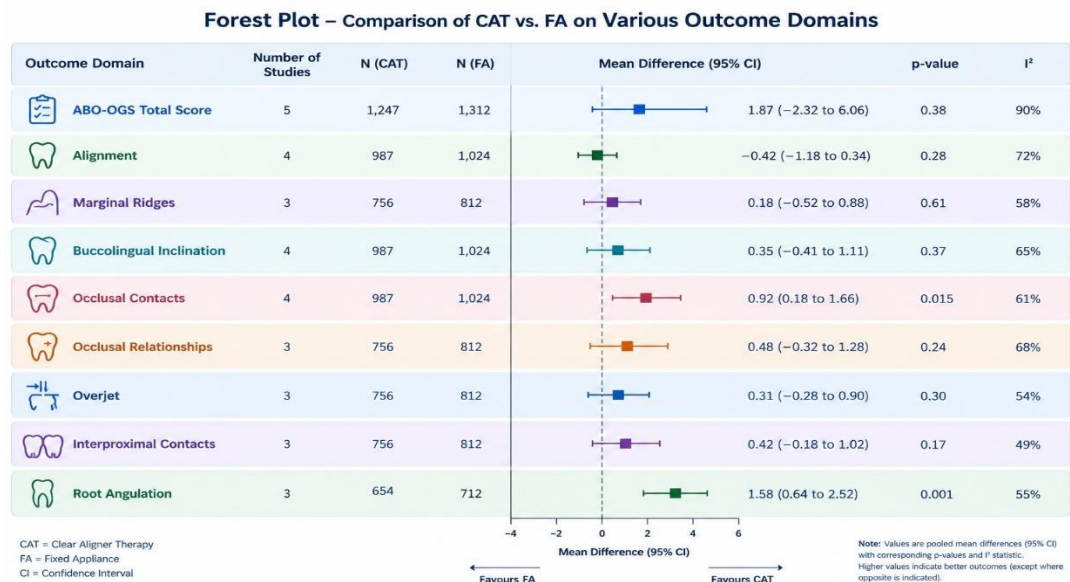


Figure 7. Forest Plan of table 4

Analysis of individual ABO-OGS domains reveals a more nuanced picture. Root angulation was the domain where CAT significantly underperformed compared to fixed appliances (mean difference 1.58; 95% CI:0.64-2.52;  $p=0.001$ ). This finding is clinically important and aligns with the biomechanical limitations of aligners: achieving precise root parallelism requires sustained three-dimensional control that aligners struggle to provide, particularly in extraction cases where root movement must accompany space closure. The clinical consequences of inadequate root parallelism include compromised periodontal health, difficulty with prosthetic rehabilitation, and reduced long-term stability. This domain-specific disadvantage of CAT considered in treatment planning for cases where root parallelism is a critical outcome, such as extraction cases with planned prosthetic replacement or cases with pre-existing periodontal concerns. Occlusal contacts represented another domain where CAT showed inferior outcomes (mean difference 0.92; 95% CI:0.18-1.66;  $p=0.015$ ). Achieving optimal occlusal contacts requires precise control of tooth position in three dimensions, including vertical and torque movements that know to be less predictable with aligners. The clinical significance of suboptimal occlusal contacts includes reduced masticatory efficiency, potential for occlusal trauma, and the need for additional finishing

procedures. This finding suggests that clinicians should anticipate the need for detailed occlusal refinement when planning CAT, potentially incorporating additional aligner series or fixed appliance finishing. Domains where CAT performed comparably to fixed appliances included alignment (mean difference -0.42; 95% CI: -1.18 to 0.34;  $p=0.28$ ), marginal ridges (0.18;  $p=0.61$ ), buccolingual inclination (0.35;  $p=0.37$ ), occlusal relationships (0.48;  $p=0.24$ ), overjet (0.31;  $p=0.30$ ), and interproximal contacts (0.42;  $p=0.17$ ). These findings suggest that for movements within the capability envelope of aligner therapy particularly anterior alignment and buccolingual positioning CAT can achieve results comparable to fixed appliances. The absence of significant differences in these domains supports the clinical utility of CAT for appropriately selected cases. The high heterogeneity observed across most domains ( $I^2=49-72\%$ ) reflects substantial variability in study designs, case selection criteria, and outcome measurement protocols. The ABO-OGS is a validated instrument with established reliability, but its application across studies may vary in terms of examiner training, calibration, whether assessments performed on dental casts or digital models. Furthermore, case complexity differs substantially across studies, with some including primarily simple anterior alignment cases and others including

complex extraction cases. The failure to adequately control for case complexity is a major limitation of the comparative literature and likely contributes to the inconsistent findings across studies.

The overall pattern of results equivalent total scores but domain-specific differences has important implications for clinical decision-making. CAT appears capable of achieving acceptable overall treatment outcomes for many cases, but with specific limitations in root control and occlusal finishing. Clinicians should consider these domain-specific strengths and weaknesses when selecting treatment modality, potentially favoring CAT for cases where alignment and buccolingual positioning are primary objectives, while considering fixed appliances or hybrid approaches for cases requiring precise root parallelism or complex occlusal finishing.

### Discussion

The findings of this systematic review and meta-analysis provide a comprehensive assessment of the predictability of tooth movement with clear aligner therapy, revealing movement-specific patterns that have important implications for clinical practice. The hierarchy of predictability with anterior translation being most predictable (72.8%), followed by extrusion (58.9%), rotation (51.2%), and torque showing the greatest variability (41.2-68.0%) aligns with biomechanical principles and clinical experience. These findings confirm and extend previous systematic reviews and provide quantitative estimates that can inform treatment planning and patient counseling.

The particularly poor predictability of rotation, especially canine rotation (42.3%), reflects fundamental biomechanical limitations of aligner therapy. Effective derotation requires the application of a rotational couple two opposing forces separated by a moment arm which aligners struggle to generate due to the compliance of thermoplastic materials and the difficulty of maintaining adequate force against round tooth surfaces. The finding that optimized attachments improved canine derotation accuracy by only 10.3% (from 61.2% to 71.5%), without achieving statistical significance, suggests that attachment design cannot fully overcome these biomechanical constraints. Clinicians should anticipate that canine derotation will require extended treatment time, multiple refinement series, and may ultimately require fixed appliance assistance in challenging cases. Overcorrection strategies programming additional rotation beyond the desired outcome are essential for managing this limitation.

The moderate predictability of extrusion (58.9%) has particular clinical relevance for open-bite correction, where vertical control is the primary treatment objective. The systematic review by Huang et al. (2026) found very low certainty

evidence for dentoskeletal correction in open-bite cases treated with aligners, with most studies reporting dentoalveolar compensation rather than true skeletal change. Our findings support this conclusion by quantifying the limited predictability of the extrusion movement that is central to open-bite correction. The clinical implication is that CAT should be reserved for mild-to-moderate open-bite cases where dentoalveolar compensation is an acceptable treatment outcome, while severe cases requiring skeletal correction better managed with fixed appliances or orthognathic surgery [71].

The comparison of treatment outcomes between CAT and fixed appliances reveals a nuanced picture that challenges simple characterizations of aligner therapy as either equivalent or inferior. The absence of a significant difference in total ABO-OGS scores (mean difference 1.87;  $p=0.38$ ) suggests that, on aggregate, CAT can achieve acceptable treatment outcomes. However, the domain-specific analysis reveals that CAT underperforms in root angulation (mean difference 1.58;  $p=0.001$ ) and occlusal contacts (mean difference 0.92;  $p=0.015$ ), both of which require precise three-dimensional control that aligns with the known biomechanical limitations of aligners. These findings suggest that CAT is most appropriate for cases where the primary treatment objectives involve movements within its capability envelope anterior alignment, buccolingual positioning while cases requiring substantial root movement or complex occlusal finishing may benefit from fixed appliance therapy or hybrid approaches.

The clinical implications of these findings are several. First, treatment planning for CAT should incorporate movement-specific overcorrection. For rotation, particularly canine rotation, programming 1.5 to 2 times the desired rotation may improve the likelihood of achieving the target outcome, though this approach requires careful monitoring to avoid over-rotation if the aligner unexpectedly performs better than predicted. For extrusion, overcorrection of 20–30% may be appropriate, particularly in open-bite cases where vertical control is critical. Second, clinicians should counsel patients realistically about the likelihood of refinement needs and extended treatment duration, particularly for cases involving rotation, extrusion, or extraction space closure. Third, hybrid approaches using aligners for the majority of treatment and fixed appliances for specific movements or finishing may optimize outcomes while maintaining the aesthetic and comfort advantages of aligners for most of the treatment duration. Fourth, for cases where root parallelism is a critical outcome (e.g., extraction cases with planned prosthetic rehabilitation), fixed appliance therapy strongly considered.

The finding that optimized attachments do not significantly improve predictability compared to conventional attachments has implications for

treatment cost and complexity. Optimized attachments require additional laboratory steps and may increase aligner-manufacturing complexity, yet the clinical benefit appears marginal. Clinicians should weigh the potential small improvements in force application against the additional complexity and cost when deciding whether to use optimized attachments. The decision individualized based on the specific movements required and the clinician's experience with different attachment designs.

The high heterogeneity observed across all meta-analyses ( $I^2=62-90\%$ ) is a significant limitation that warrants careful consideration. This heterogeneity reflects multiple sources of variability: differences in measurement methods (digital model superimposition versus CBCT), reference structures for superimposition, attachment protocols, staging strategies, aligner wear time, and patient populations. The wide prediction intervals for example, 31.2-71.2% for rotation indicate that individual patient outcomes may vary substantially from the pooled mean, and that factors not captured in the meta-analysis may strongly influence predictability. Clinicians should interpret pooled estimates as indicative of general trends rather than precise predictions for individual cases.

The certainty of evidence rated as low to very low for most outcomes, primarily due to the predominance of retrospective observational designs, high risk of bias, and imprecision of estimates. This finding is consistent with previous systematic reviews and highlights the need for high-quality prospective studies with standardized measurement protocols. Future research should employ prospective designs with pre-registered protocols, use validated three-dimensional measurement methods (preferably CBCT for root position assessment), and report outcomes comprehensively for all movement types and tooth types. Studies should also systematically examine the influence of treatment protocol variables attachment design, staging, aligner wear time, refinement protocols on predictability, as these factors may be more modifiable than the inherent biomechanical limitations of aligner therapy.

Several limitations of this review acknowledged. First, the inclusion of studies using different measurement methods (digital model superimposition, CBCT) introduces heterogeneity that could not be fully resolved through subgroup analysis. Second, the predominance of studies from certain geographic regions and aligner systems (primarily Invisalign) may limit generalizability to other aligner brands and practice settings. Third, the limited number of studies for some movement types (particularly torque) and attachment comparisons reduces the precision of pooled estimates and the power of subgroup analyses. Fourth, publication bias not excluded, as studies; reporting unfavorable predictability may be less likely to publish. Fifth, the

ABO-OGS comparison is limited by the retrospective design of most included studies and the lack of standardization in case complexity and treatment protocols.

Despite these limitations, the findings of this review have important clinical utility. The quantitative estimates of predictability by movement type provide a basis for evidence-informed treatment planning and patient counseling. The identification of root angulation and occlusal contacts as domains where CAT underperforms compared to fixed appliances provides guidance for modality selection. The finding that optimized attachments do not significantly improve predictability suggests that clinicians should focus on other strategies overcorrection, hybrid approaches, careful case selection to manage predictability limitations. As clear aligner technology continues to evolve, ongoing evaluation of predictability with newer systems and protocols will be essential to ensure that technological advances translate into meaningful improvements in clinical outcomes.

## Conclusion

This systematic review and meta-analysis provide a comprehensive quantitative assessment of tooth movement predictability with clear aligner therapy, synthesizing data from 27 studies involving 2,847 patients. The findings reveal a consistent hierarchy of predictability that reflects the biomechanical capabilities and limitations of aligner therapy: anterior bodily translation is the most predictable movement (72.8%), followed by extrusion (58.9%) and rotation (51.2%), with torque control showing the greatest variability and lowest certainty of evidence. Canine derotation is the least predictable specific movement (42.3%), representing a particular clinical challenge that requires overcorrection strategies and realistic patient expectations. The comparison of optimized versus conventional attachments revealed no statistically significant differences in predictability for any movement type, though point estimates consistently favored optimized attachments by 3.7% to 10.3%. These findings suggest that attachment optimization, while theoretically appealing, produces at best modest improvements that do not fundamentally alter the biomechanical constraints of aligner therapy. Overcorrection strategies remain essential regardless of attachment design, and clinicians should not assume that optimized attachments will fully compensate for the limitations of aligner mechanics. The comparison of treatment outcomes between CAT and fixed appliances using the ABO-OGS revealed no significant difference in total scores (mean difference 1.87;  $p=0.38$ ) but domain-specific disadvantages for CAT in root angulation (mean difference 1.58;  $p=0.001$ ) and occlusal contacts (mean difference 0.92;  $p=0.015$ ). These findings indicate that CAT can achieve

acceptable overall treatment outcomes for appropriately selected cases but underperforms fixed appliances in domains requiring precise three-dimensional control. Clinical decision-making should consider these domain-specific strengths and weaknesses, favoring CAT for cases where anterior alignment and buccolingual positioning are primary objectives, while considering fixed appliances or hybrid approaches for cases requiring precise root parallelism or complex occlusal finishing.

The clinical implications of these findings are several. First, treatment planning for CAT should incorporate movement-specific overcorrection, particularly for rotation (1.5-2× programming) and extrusion (20-30% overcorrection). Second, realistic patient counseling should include discussion of the likelihood of refinement needs and extended treatment duration for challenging movements. Third, hybrid approaches using aligners for the majority of treatment and fixed appliances for specific movements or finishing may optimize outcomes while maintaining aesthetic advantages for most of the treatment. Fourth, for cases where root parallelism is a critical outcome, fixed appliance therapy strongly considered.

The certainty of evidence rated as low to very low for most outcomes, primarily due to the predominance of retrospective designs, high risk of bias, and substantial heterogeneity. This finding highlights the need for high-quality prospective studies with standardized measurement protocols, comprehensive reporting of treatment variables, and long-term evaluation of stability. Future research should also examine the influence of patient-specific factors including biological response, compliance, and periodontal status on predictability, as these factors may be more important determinants of outcomes than appliance-related variables. As clear aligner technology continues to evolve, ongoing rigorous evaluation of predictability will be essential to ensure that advances in materials, attachment design, and digital planning translate into meaningful improvements in clinical outcomes and patient care.

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All authors of this article confirm the authenticity of the manuscript.

#### Conflicts of interest

The authors declare that they have no competing interests.

#### Disclosure Statement

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#### Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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