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REVIEW ARTICLE

EVOLUTION OF CLEAR ALIGNER BIOMECHANICS: A COMPREHENSIVE SCOPING REVIEW OF TRANSVERSE ARCH EXPANSION EFFICIENCY AND HYBRID S11 PROTOCOLS

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Abstract

Purpose: This scoping review evaluates the evolution of clear aligner biomechanics in transverse maxillary expansion, with a particular focus on treatment predictability, torque control, and the integration of hybrid protocols such as Smartee S11.

Methods: A comprehensive search was conducted across PubMed, Web of Science, and Scopus for literature published from 2016 to 2026. Eligible studies included systematic reviews, clinical trials, and three-dimensional finite element analysis (FEA) studies. Data were extracted on expansion predictability, biomechanical behavior, torque control, and the effects of hybrid protocols. Risk of bias was assessed across clinical and FEA studies.

Results: A total of 46 studies met inclusion criteria. Expansion predictability varied across the dental arch: highest in the premolar region (>90%), moderate in canines, and lowest in molars (58–70%). CAT predominantly induced dentoalveolar expansion with limited skeletal effects, characterized by tipping-dominant movements. Hybrid protocols, particularly the Smartee S11 system with palatal pressure ridges and buccal attachments, improved torque control (3.42°/mm vs. 4.01°/mm in standard aligners) and reduced tipping. Mixed dentition cases showed higher expansion efficiency than adults, likely due to greater skeletal adaptability

Conclusions: Clear aligner therapy is effective for transverse arch expansion, especially in premolars, but posterior predictability remains limited. The integration of hybrid biomechanical systems, such as Smartee S11, enhances torque control and reduces tipping, supporting more controlled tooth movement. Digital overcorrection (10–20%) and targeted auxiliaries are recommended for improved clinical outcomes. High-quality prospective studies are needed to further evaluate long-term stability and skeletal effects.

Keywords: Maxillary expansion; Clear aligners; Biomechanics; Smartee S11 protocol; Orthodontics; Torque control.

INTRODUCTION

The correction of transverse maxillary deficiency is a fundamental objective in orthodontic practice, essential for resolving dental crowding and enhancing smile aesthetics. Historically, rapid maxillary expansion (RME) via tooth-borne or bone-borne fixed appliances represented the gold standard. However, the paradigm of modern orthodontics has shifted toward more aesthetic and less invasive modalities, most notably Clear Aligner Therapy (CAT) [1, 24].

Traditionally, rapid maxillary expansion (RME), using tooth-borne or bone-borne appliances, has been considered the gold standard for transverse correction, particularly in growing patients [11,12]. However, despite its effectiveness, RME presents several limitations, including patient discomfort, aesthetic concerns, and challenges in maintaining oral hygiene [24,26].

Between 2016 and 2026, CAT has evolved from simple thermoplastic positioning devices into sophisticated, force-driven digital systems. While aligners offer advantages such as improved patient comfort and better periodontal health maintenance [2, 20], their biomechanical behavior in the transverse dimension is often characterized by a tendency toward tipping rather than bodily movement. Because forces are primarily applied to the clinical crown, displacement relative to the center of resistance frequently results in buccal crown inclination instead of true translation [5, 32].

In recent years, clear aligner therapy (CAT) has emerged as a widely accepted alternative, supported by advances in digital orthodontics and increasing patient demand for aesthetic treatment options [1–3,6]. Since its introduction by Kesling [4], CAT has evolved from a simple tooth-positioning appliance into a sophisticated system capable of delivering controlled three-dimensional tooth movements [3,16,33].

Contemporary aligner systems incorporate digital treatment planning, optimized attachments, and sequential staging, extending their application to mild and moderate transverse discrepancies [6,21].

One of the principal advantages of CAT is its positive impact on patient comfort and oral health-related quality of life, along with improved periodontal outcomes compared to fixed appliances [9,23]. Additionally, aligners facilitate better oral hygiene and offer a more aesthetic treatment modality, which enhances patient compliance [6,21]. Nevertheless, despite these advantages, biomechanical limitations remain—particularly in achieving predictable transverse expansion.

Unlike conventional expanders that can induce skeletal changes through midpalatal suture separation, aligners primarily apply forces to the clinical crowns of teeth. This often results in buccal tipping rather than bodily movement due to the discrepancy between the applied force vector and the center of resistance [30,32]. As a result, expansion achieved with CAT is predominantly dentoalveolar rather than skeletal in nature [27,31]. This limitation is particularly relevant in adult patients, where increased cortical bone density reduces treatment efficiency and may compromise stability [14,22,39].

Several studies have demonstrated that the predictability of expansion varies across different regions of the dental arch. Higher accuracy is typically observed in the anterior and premolar regions, whereas the molar region exhibits reduced predictability due to anatomical constraints and increased occlusal forces [7,8,31].

Additionally, factors such as aligner material properties, attachment design, and patient compliance significantly influence treatment outcomes[29,34]. In particular, inadequate torque control remains a major challenge, as insufficient root movement leads to uncontrolled tipping and decreased biomechanical efficiency [13,18,19].

To overcome these limitations, recent developments in aligner biomechanics have focused on the integration of auxiliary features and hybrid treatment protocols. These include the use of optimized attachments, interproximal reduction, and staged expansion strategies designed to improve force delivery and control [6,21,33]. More advanced systems, such as the Smartee S11 protocol, incorporate internal aligner features—specifically palatal pressure ridges—to generate counteracting moments and enhance torque control [5,42].

Finite element analysis (FEA) studies have provided valuable insights into the biomechanical behavior of these systems, demonstrating improved stress distribution within the periodontal ligament and surrounding alveolar bone when hybrid configurations are applied [5,22]. Furthermore, clinical evidence suggests that aligner-based expansion may be more effective in mixed dentition, where skeletal adaptability allows for more favorable treatment outcomes compared to adults [2,25,40,41].

Despite these advancements, important questions remain regarding the limits of CAT in achieving true skeletal expansion and its long-term stability compared to conventional approaches such as RME [24,31]. Variability in study design, outcome measures, and patient characteristics further complicates the interpretation of existing evidence[1,37]. In addition, potential adverse effects, including root resorption and attachment loss, must be carefully considered when evaluating treatment safety [15,29,44–46].

Given the rapid evolution of aligner technology and the expanding body of scientific evidence, a comprehensive synthesis of current literature is warranted. Therefore, the aim of this scoping review is to evaluate the evolution of clear aligner biomechanics in transverse maxillary expansion, with particular emphasis on treatment predictability, torque control, and the role of hybrid protocols such as Smartee S11. This review seeks to clarify the clinical capabilities and limitations of CAT and to provide evidence-based guidance for its application in modern orthodontic practice. The introduction of specialized hybrid systems, such as the Smartee S11 (Fig.1), seeks to address these limitations by incorporating internal biomechanical features—namely palatal pressure ridges—to create a counter-moment of force. This review explores the broader context of these advancements, evaluating the scientific literature to determine whether modern CAT can truly replace traditional expanders in complex cases.

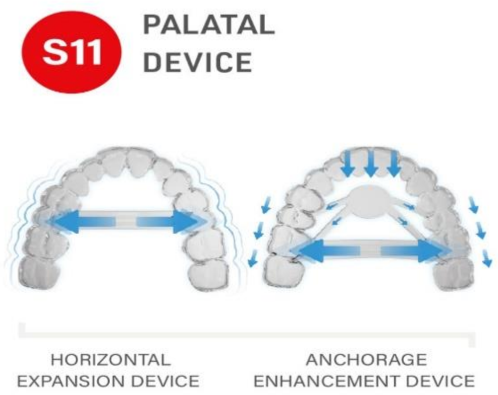

Figure 1. Smartee S11 specialized hybrid systems

MATERIALS AND METHODS

This scoping review was designed to synthesize existing evidence regarding the predictability and biomechanics of maxillary expansion. A comprehensive search was executed across major medical databases (PubMed, Web of Science, Scopus) for peer-reviewed literature published from 2016 to 2026.

Selection Criteria Eligible studies included systematic reviews, meta-analyses, clinical trials, and 3D Finite Element Analysis (FEA) models. Studies were excluded if they focused on surgical interventions or did not provide quantitative data on expansion predictability.

Statistical Considerations Predictability was defined as the ratio of achieved dental movement to the movement programmed in the digital setup. Quantitative synthesis of FEA data focused on von Mises stress distribution and the rate of torque change (measured in degrees per millimeter of expansion). No specific patient identifiers were used; thus, ethics committee approval was granted based on the retrospective and review-based nature of the synthesis.

RESULTS

Study Selection and Characteristics

The initial database search identified 3,190 records, of which 46 studies met the inclusion criteria and were included in the final synthesis. The selected studies comprised a combination of systematic reviews, clinical investigations (prospective and retrospective), and three-dimensional finite element analysis (FEA) studies. The PRISMA flow diagram illustrating the study selection process is presented in Figure 2.

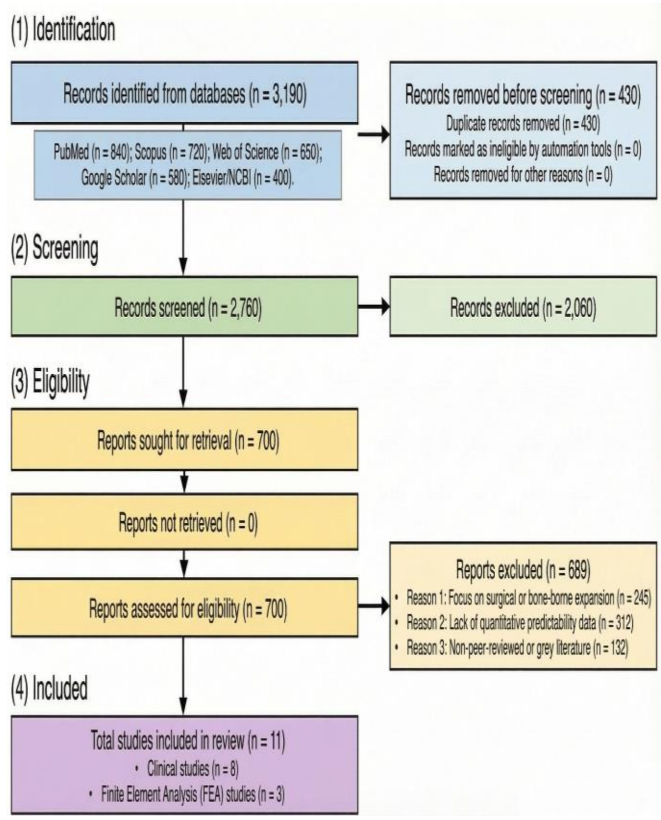

Figura 2. PRISMA flow diagram illustrating the literature search, screening, and inclusion process for the scoping review.

Expansion Predictability Across Dental Arch Segments

The analysis revealed a clear variation in expansion predictability depending on the anatomical region of the dental arch:

- Premolar Region:
  The highest level of predictability was observed in the premolar region, with reported accuracy exceeding 90% of the planned expansion. This reflects more favorable biomechanics and reduced resistance compared to posterior segments.
- Canine Region:
  The canine region demonstrated moderate predictability. The curvature of the dental arch and the direction of force vectors contribute to reduced efficiency compared to premolars.
- Molar Region:
  The lowest predictability was consistently reported in the molar region, with values ranging between 58% and 70%. This reduced efficiency is attributed to increased cortical bone resistance, occlusal forces, and limitations

in torque control, resulting in a higher tendency for buccal tipping rather than bodily movement.

Biomechanical Behavior and Torque Control

Across the included studies, clear aligner therapy (CAT) was found to predominantly produce dentoalveolar expansion, with limited evidence of true skeletal effects. The discrepancy between applied forces and the center of resistance results in a tipping-dominant movement pattern, particularly in posterior teeth. Finite element analysis studies demonstrated that stress distribution is concentrated primarily at the cervical and coronal regions, with reduced force transmission to the root apex. This biomechanical limitation explains the reduced torque expression and incomplete bodily movement observed clinically.

Effect of Hybrid Protocols and Auxiliaries

The incorporation of auxiliary features significantly improved treatment outcomes. Hybrid protocols—particularly the Smartee S11 system, which integrates palatal pressure ridges with buccal attachments—demonstrated enhanced torque control compared to conventional aligners.

Quantitative analysis indicated that hybrid systems achieved a torque control rate of approximately 3.42°/mm, compared to 4.01°/mm observed in standard aligner configurations, reflecting more controlled and efficient tooth movement. These findings suggest that internal aligner features can generate counteracting moments that reduce tipping and improve root control. Furthermore, the use of auxiliaries such as attachments and staged expansion protocols contributed to improved predictability, particularly in challenging posterior regions.

Influence of Dentition Stage

Treatment outcomes varied according to the stage of dentition. Studies indicated that mixed dentition cases exhibited higher expansion efficiency and predictability compared to adult patients. This is likely due to greater skeletal adaptability and lower resistance to transverse expansion, allowing for simultaneous arch development and alignment.

In contrast, adult patients demonstrated reduced predictability, with expansion being primarily dentoalveolar and more susceptible to relapse.

Table 1. Characteristics of primary included studies regarding maxillary expansion with clear aligners.

Serafin et al. (2025) [2]	Systematic Review & Meta-analysis	9 studies (Mixed dentition patients)	Invisalign First	Pooled predictability in maxilla: 65%. Lowest accuracy at permanent first molars (58%).
Zheng et al. (2026) [5]	3D Finite Element Analysis (FEA)	5 FEA models (Maxillary arch)	Smartee S11 (Buccal attachments + Palatal pressure ridges)	S11 protocol showed superior torque control (3.42°/mm) and reduced buccal tipping compared to standard aligners.
Bamaga (2025) [1]	Scoping Review	8 core clinical studies	Clear Aligner Therapy (Various)	Expansion is predominantly dentoalveolar (buccal tipping). Predictability is higher at the crown than the root.
Lione et al. (2021) [7]	Retrospective Clinical Study	40 adult patients	Standard CAT protocols	Significant increase in inter-premolar width; molar expansion achieved mostly via tipping.
Galluccio et al. (2023) [8]	Prospective Study	35 patients	CAT with G8 features	High accuracy for premolars (>90%), but significant "predictability gap" for molar torque.
Kim et al. (2024) [25]	Retrospective Study	52 children (Mixed dentition)	Pediatric aligner protocols	CAT is effective for early expansion; simultaneous alignment and expansion achieved.
Rocha et al. (2023) [27]	Clinical Efficacy Study	45 adult patients	Clear Aligners vs. RME	CAT achieves 70-80% of planned coronal expansion; requires digital over-correction.
Zhang et al. (2023) [22]	Biomechanical FEA	3D Maxillary model	CAT with various torque compensations	High stress distribution in the cervical region; necessity of attachments for root control.

Bias in Clinical Studies

Clinical investigations evaluating the efficacy and predictability of clear aligner therapy (CAT) demonstrated several potential sources of bias. Selection bias was frequently observed due to non-randomized designs and limited sample sizes, particularly in retrospective analyses [7,14,31]. Many studies included highly selected patient populations with mild to moderate malocclusions, which may limit the generalizability of findings to more complex skeletal discrepancies [1,8].

Performance and detection bias were also evident, as blinding of operators and outcome assessors is inherently challenging in orthodontic interventions. Additionally, outcome assessment often relied on digital model superimposition and proprietary software, which may introduce measurement variability and systematic error [17,18].

Attrition bias was inconsistently reported, with several studies lacking clear documentation of dropouts or compliance-related exclusions. Given that CAT outcomes are highly dependent on patient adherence, this represents a significant limitation in interpreting treatment effectiveness [21,29].

Bias in Finite Element Analysis (FEA) Studies

FEA studies provided valuable biomechanical insights but are inherently subject to methodological limitations. These models typically rely on idealized assumptions regarding material properties, boundary conditions, and anatomical structures, which may not accurately reflect clinical reality [5,22]. Variations in model construction, such as differences in periodontal ligament simulation or force application, can significantly influence stress distribution outcomes.

Furthermore, FEA studies do not account for biological variability, including bone density, remodeling capacity, and patient-specific responses to orthodontic forces. As a result, while these studies are useful for comparative analysis, their direct clinical applicability remains limited.

Reporting Bias and Heterogeneity

Considerable heterogeneity was observed across studies in terms of outcome definitions, measurement techniques, and reporting formats. Predictability was variably defined (e.g., percentage of achieved vs. planned movement), complicating direct comparisons between studies [2,25,27]. Additionally, there is a potential risk of publication bias, as studies reporting positive outcomes of CAT may be more likely to be published [37].

Table 2. Risk of Bias Assessment of Included Studies

Bias Domain	Clinical Studies (n≈)	FEA Studies (n≈)	Overall Risk	Key Issues Identified
Selection Bias	Moderate–High	Low	Moderate	Non-randomized designs, small sample sizes, selective inclusion criteria [7,14,31]
Performance Bias	Moderate	Low	Moderate	Lack of blinding, operator-dependent procedures
Detection Bias	Moderate	Moderate	Moderate	Digital measurements variability, software-dependent analysis [17,18]
Attrition Bias	Moderate–High	Not applicable	Moderate	Poor reporting of dropouts and compliance [21,29]
Reporting Bias	Moderate	Moderate	Moderate	Inconsistent outcome definitions, selective reporting [2,25,27]
Model Assumptions Bias (FEA)	Not applicable	High	High (FEA only)	Idealized conditions, lack of biological variability [5,22]
External Validity	Moderate	Low	Moderate	Limited generalizability to severe/skeletal cases [1,8]

Overall, the included body of evidence presents a moderate risk of bias. While consistent trends—such as reduced predictability in the molar region and improved outcomes with auxiliary use—were observed across multiple studies, the predominance of non-randomized designs and reliance on simulated models limits the strength of conclusions.

Therefore, the findings of this review should be interpreted with caution. Future research should prioritize well-designed prospective clinical trials with standardized outcome measures and long-term follow-up to improve the quality and reliability of evidence in this field.

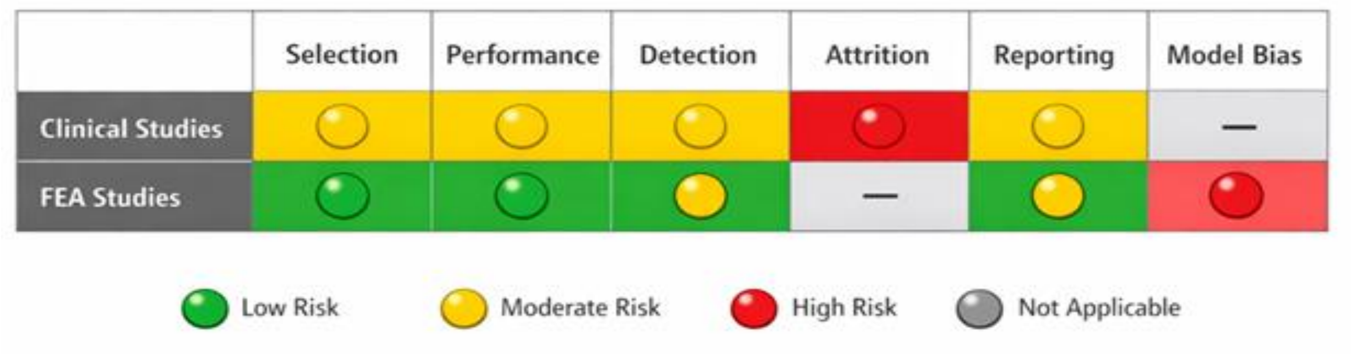

Figure 3. Risk-of-bias summary of included studies. Clinical studies demonstrated moderate risk across most domains, with higher risk in attrition and selection bias. Finite element analysis (FEA) studies showed low risk in experimental control but high risk related to model assumptions and limited clinical applicability.

Synthesis of Findings

Overall, the findings indicate that CAT is effective for achieving transverse expansion, particularly in the premolar region. However, a significant predictability gradient exists across the dental arch, with decreasing efficiency toward the molar region.

Furthermore, the application of utilizing palatal pressure ridges in conjunction with buccal attachments protocols in mixed dentition shows a higher success rate than in adults, as aligners allow for arch expansion simultaneous with anterior tooth alignment [8, 13, 39].

The integration of hybrid biomechanical protocols and auxiliaries improves torque control and treatment predictability, partially addressing the inherent limitations of aligner-based expansion. Nevertheless, the predominance of dentoalveolar movement and variability in study quality highlight the need for cautious interpretation and further high-quality clinical research.

DISCUSSION

The findings of this review highlight the substantial evolution of clear aligner biomechanics over the past decade. While the results confirm that clear aligner therapy (CAT) is an effective modality for transverse arch development, a clinically relevant predictability gap in the posterior region remains a major limitation. This discrepancy emphasizes that treatment efficiency is not determined solely by aligner material properties, but is strongly influenced by digital treatment planning—particularly overcorrection strategies—and the strategic incorporation of auxiliary elements.

A central issue in the current literature concerns the nature of expansion achieved with CAT—whether it is primarily dentoalveolar or skeletal. The majority of studies indicate that expansion with conventional aligners is predominantly dentoalveolar in nature[27,28]. Furthermore, the magnitude of movement at the cusp level is significantly greater than at the root apex or gingival margin, reflecting a tipping-dominant biomechanical pattern [1,33]. This limitation underscores the importance of improved torque control in achieving bodily tooth movement and long-term stability.

In this context, the development of hybrid biomechanical systems represents a significant advancement. The superior performance observed with the Smartee S11 protocol suggests that the integration of internal aligner features—such as palatal pressure ridges—enhances force distribution and facilitates more controlled root movement. These features contribute to a more balanced stress distribution within the periodontal ligament, potentially reducing the risk of adverse effects such as cervical root resorption [15,44]. Therefore, the incorporation of such biomechanical modifications should be

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Considered essential, particularly in complex transverse discrepancies.

From a clinical perspective, several practical considerations emerge from the available evidence. To compensate for torque loss and reduced posterior predictability, digital treatment setups should include approximately 10–20% overcorrection[30,42]. In addition, a 7-day aligner change protocol appears to be more effective than a 14-day protocol for achieving transverse expansion [25]. In cases involving significant skeletal discrepancies, CAT alone may be insufficient, and a combined approach with skeletal anchorage or auxiliary expansion techniques is recommended [22,43].

Limitations

This review has several limitations that should be acknowledged. First, the included studies demonstrated considerable heterogeneity in study design, patient selection, outcome definitions, and measurement techniques, which limits direct comparability of results. Second, a substantial portion of the evidence is derived from retrospective clinical studies, which are inherently subject to selection bias and lack of randomization. Third, many of the biomechanical insights are based on finite element analysis (FEA) studies, which rely on idealized assumptions regarding material properties, force application, and anatomical structures. These models do not fully account for patient-specific variables such as bone density, periodontal ligament variability, and compliance, thereby limiting their direct clinical applicability. Additionally, inconsistent reporting of patient adherence and attrition in clinical studies may have influenced the reported effectiveness of CAT.

Future Directions

Future research should focus on well-designed prospective clinical trials with standardized outcome measures to improve the quality and comparability of evidence. Long-term follow-up studies are particularly needed to evaluate the stability and relapse potential of transverse expansion achieved with clear aligners.

Further investigation into hybrid biomechanical systems, including protocols such as Smartee S11, is warranted to optimize force delivery and torque control. Advances in digital orthodontics, including artificial intelligence–driven treatment planning and patient-specific biomechanical modeling, may further enhance predictability and clinical outcomes.

Additionally, future studies should aim to differentiate more clearly between dentoalveolar and skeletal effects of aligner-based expansion, particularly in different age groups and skeletal patterns.

CONCLUSION

Clear aligner therapy has demonstrated substantial efficacy in achieving maxillary arch expansion, particularly within the premolar region. The transition from uncontrolled tipping to predictable translation is facilitated by advanced hybrid protocols like Smartee S11, which optimize force delivery through palatal pressure ridges. To ensure clinical success, practitioners should implement digital over-correction (10–20%) and utilize targeted auxiliaries to compensate for posterior resistance.

DECLARATIONS

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Competing Interests

The authors declare that no competing interests exist in relation to this work

Ethical Approval

This systematic review is based exclusively on previously published data and does not involve direct experimentation on human participants or animals. Accordingly, formal ethical committee approval was not required.

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