Universidad Europea

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Degree in Dentistry

EFFECTIVENESS OF ORTHODONTIC MOVEMENTS WITH ALIGNERS

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RESUMEN

Introducción: La terapia con alineadores transparentes se ha convertido en una opción de tratamiento ortodóncico más popular debido a su carácter estético y removible. Sin embargo, las discrepancias entre los movimientos dentarios planificados digitalmente y los obtenidos clínicamente siguen siendo una preocupación clínica relevante.

Objetivo: Evaluar la predictibilidad de los diferentes movimientos dentarios con alineadores transparentes (inclinación, rotación, movimientos de traslación, intrusión y extrusión), comparando los movimientos planificados digitalmente con los logrados clínicamente.

Materiales y métodos: Se realizó una revisión sistemática siguiendo las directrices PRISMA. Se realiza una búsqueda en PubMed, Medline y bases de datos universitarias. Se incluyeron estudios clínicos publicados entre 2016 y 2026 que evaluaban las diferencias cuantitativas entre los movimientos dentarios planificados y los alcanzados con alineadores. Se incluyeron un total de 15 estudios, con tamaños que oscilaron entre 10 y 206 pacientes.

Resultados: Los resultados mostraron una tendencia hacia la subexpresión de los movimientos planificados. La inclinación fue el movimiento con mayor predictibilidad, mientras que las traslaciones, especialmente en dirección mesiodistal, y la extrusión presentaron la menor precisión. La rotación y el torque mostraron resultados variables dependiendo del tipo de diente y de la magnitud del movimiento. La expansión transversal fue moderadamente predecible y, en muchos casos, se produjo mediante inclinación dental en lugar de un desplazamiento corporal real. Los resultados del tratamiento estuvieron influenciados por la magnitud y complejidad del movimiento planificado, así como por la colaboración del paciente.

Conclusiones: La terapia con alineadores transparentes presenta una efectividad global, con una predictibilidad altamente dependiente del tipo y la magnitud del movimiento realizado. La planificación digital tiende a sobreestimar los resultados clínicos. Una adecuada selección de casos y planificación biomecánica, junto con el uso de sobre correcciones, auxiliares y fases de refinamiento, son esenciales para mejorar la precisión del tratamiento y alcanzar resultados clínicos óptimos.

PALABRAS CLAVE

Odontología, ortodoncia, alineadores, eficacia, movimientos

ABSTRACT

Introduction: Clear aligner therapy has become an increasingly popular orthodontic treatment option due to its aesthetic and removable nature. However, discrepancies between digitally planned and clinically achieved tooth movements remain a relevant clinical concern.

Objective: To evaluate the predictability of the different teeth movements with clear aligners (tipping, rotation, bodily movements, intrusion and extrusion) comparing between digital treatment plan teeth movements vs clinical teeth movement.

Materials and methods: A systematic review was conducted following PRISMA guidelines. A comprehensive literature search was performed using PubMed, Medline, and university databases. Clinical studies evaluating the quantitative differences between planned and achieved tooth movements with clear aligners published between 2016 and 2026 were included. A total of 15 studies were included, with sample sizes ranging from 10 to 206 patients.

Results: The results showed a consistent tendency toward underexpression of planned movements. Tipping demonstrated the highest predictability, whereas bodily translations, particularly in the mesiodistal direction, and extrusion showed the lowest accuracy. Rotation and torque presented variable results depending on tooth type and movement magnitude. Transverse expansion was moderately predictable and often occurred through dental tipping rather than true bodily movement. Treatment outcomes were influenced by the magnitude and complexity of the planned movement, as well as patient compliance.

Conclusions: Clear aligner therapy demonstrates overall effectiveness, with predictability highly dependent on the type and amount of movement performed. Digital treatment planning tends to overestimate clinical outcomes. Careful case selection and biomechanical planning coupled with the use of overcorrections, auxiliaries and refinement stages are essential to improve treatment accuracy and achieve optimal clinical results.

KEYWORDS

Dentistry, orthodontics, aligners, effectiveness, movements

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1. INTRODUCTION

1.1 Background

1.1.1 Introduction to clear aligners therapy

Orthodontic treatments are realized with the intention of modifying the position of teeth in a three-dimensional space using controlled and predictable methods to achieve a stable, functional and aesthetic result. Clear aligners therapy was developed as a removable approach to orthodontics during which a series of custom fit and manufactured plastic aligners are used in a sequence using progressive tray shapes to create intentional incremental tooth movements until the planned functional and esthetic outcomes are reached (1).

Initially introduced in 1999 as the Invisalign system for the exclusive use of orthodontists' clear aligners fast transformed the way clinicians and patients conceived their orthodontic treatments due to combination of 3D digital planning with removable aligners; making it a more comfortable, esthetic and pleasant alternative to traditional orthodontics with fixed appliances. Clear aligners therapy workflow integrates 3D intraoral scanning, virtual treatment planning and a staging of the movements that will be planned thanks to the dedicated software, and a series of custom thermoformed aligner trays will then be manufactured for the patient to wear them in accordance with the designed schedule (2).

1.1.2 Clear aligner therapy design evolution

With time, clear aligners therapy only improved gaining widespread popularity among both patients and dentists, thanks to, the coupling of high-resolution digital imaging, computer aided design/ computer aided manufacturing (CAD/CAM) in specialized software and the use of evidence-based biomechanics. Clear aligner therapy therefore is based on the planification of different types of movements in the design software (translation movements, tipping, rotation, torque, vertical movements) and its application on the patient (3). The workflow is based on the expectation the movement visualized digitally will be accurately represented clinically, however, discrepancies are often observed between the virtual planning on the software and the actual result achieved in the patient, resulting sometimes in imperfect results (4). Clinically, these differences between the achieved movements with clear aligners therapy and the planned movements, especially relating to their effectiveness, accuracy and predictability are essential

to achieve a correct case selection, according to which movements we will be able to achieve using only clear aligners; as well as to integrate it in our planning strategy with the use of attachments cemented on the teeth, over-correction or the implementation of staging changes in the sequence of trays used. (5).

Careful planification, the use of auxiliary features and refinement strategies allowed clear aligners therapy to achieve a better effectiveness accuracy and predictability, reaching according to contemporary studies a moderate overall accuracy that is highly dependent on the tooth treated and the type of movement performed (6).

1.2 Justification

1.2.1 Clinical relevance

In recent years the use of clear aligners therapy has greatly increased worldwide, with a study conducted amongst 254 general dentists in Australia showing that more than 65% of them provided clear aligners therapy (7), and an estimated rate of use by 65-95% of orthodontists in surveys performed across multiple countries with aligner cases representing 25-30% of the orthodontists' caseload. This increase in use of clear aligners therapy is partly due to the advances integrated in the technique as well as the increasing number of systems available for clinical use (8-10).

Advances in the technique of clear aligners therapy allowed it to move from the managing of mild malocclusion to the treatment of cases of increasing complexity, however the differences in the digital plans compared to the results achieved can have important impact on the outcome of the treatment by delaying it, affecting its stability or causing the need for additional refinements (11).

Previous systematic reviews conducted highlighted that not all movement have the same accuracy and predictability in clear aligners therapy, movements like tipping and small alignments are achieved quite successfully with the clear aligners technique whereas more complex displacements like bodily translation, vertical movement (intrusion/ extrusion), rotations or a demanding root torque modification were often unpredictable both in their accuracy and predictability (12, 13). Recent data also states that the accuracy of the movement achieved is highly dependent on the tooth treated, diminishing distally along the arch with very little results in second molars displacements (4).

The influence the digital prediction made by the software has on the treatment plan made by the clinician and on both their expectations and the patients, makes it essential to find a way to

quantify the gap present in the digital plan and clinical results achieved for each movement in clear aligners therapy to improve the clinical decision making and avoid possible treatment changes or refinements in the future (14).

1.2.2 Current gap in knowledge

In recent years, multiple reviews highlighted the variations across studies often caused by differences in the definitions of movement metrics or inconsistencies in the comparison and reporting between planned movements and the ones achieved (11). Gaps in the current literature included under-representation of the influence that different software could have on the predicted movements and a lack of quantification of the movement types and tooth classes (15).

Recently new methods are being used to obtain improved more accurate measurements like 3D superimposition with the use of anatomical landmarks however, these are still not widely adopted, therefore a standardization of the measurements is yet to be achieved (16). As a result, many practitioners using these systems rely on the digital predictions providing by the software adding over-corrections or auxiliaries with no movement specific consensus, when a correct and comprehensive understanding of the biomechanics is essential for correct treatment planning while considering the limitations of the system for what is clinically achievable (13,17).

1.3 Literature review

1.3.1 Current concepts and digital planning in clear aligners therapy

The biomechanical behavior of clear aligner therapy is based on the transmission of forces through thermoformed plastic polymers and intermittent surface contact with teeth and the attachments cemented on the surface of their crowns, coupled with staging and changes of aligners at a predetermined interval to modulate the forces applied over time (6). Although aligners can successfully correct certain types of malocclusions, the extent to which the movements previously planned digitally translate clinically varies according to the system used or the complexity of the case, with characteristics limitations being present in torque, rotation control and vertical movements (14, 18).

The virtual setups that are achieved in the software by segmenting the teeth and simulating movement sequences result in a predicted goal-point used as both a communication method between the patient and the dentist and a quantitative metric for treatment planning and the results we should be able to achieve (16). Still, when compared predicted and achieved teeth positions at a set point consistently demonstrated inaccuracies of different ranges according to the type of movement performed and the tooth the forces were applied on (19).

A recent systematized review from 2025 showcases that mesiodistal molar movements can be achieved with a moderate predictability of around 61% when adequate biomechanics were used (20). However, the ranges of predictability are wide and highly dependent on the measurement methods used, the heterogeneity in aligner trays sequences, schedules and the use of auxiliary features which complicates the comparison of estimates and highlights the need for standardized settings to obtain accurate comparisons (14).

1.3.2 Effectiveness, accuracy and predictability of orthodontic movements

A reliable prospective study conducted in 2022 found out that the accuracy of teeth movements decreases the more distally the tooth is positioned in the arch, with the movements of second molars going largely unexpressed (4). Another article published in 2025 stated that the orthodontic movements with the highest accuracy and predictability in clear aligners therapy are limited tipping and small translation bodily movements, whereas vertical movements such as intrusion and extrusion and complex rotation cases still presented a high unreliability (21). An additional longitudinal clinical study from 2025 emphasizes the significant discrepancies between planned and achieved movements while at the same time highlighting the differences in outcomes obtained according to the brand of the system used, showing that the specific algorithm and material used matter (18).

The most common teeth movements executed in orthodontics are translations, rotations, tipping, torque movements and vertical movements. Among these movements, rotations are usually seen as the least reliable ones with an estimated accuracy of less than 80% (22) , true torque movements were considered a challenge with discrepancies remaining despite the use of modern protocols (23) and vertical movements (intrusion and extrusion) showed a great variability with a high accuracy in the intrusion of lower incisors but a lower one in cases of extrusions, on the other hand tipping crown movements were seen as highly precise with an accuracy of up to 95% (11, 24) .

Across these movements, comparisons between planned movements and clinical outcome show that software predictions tend to overestimate the potential clinical expression of the movement, these are especially relevant for rotations, torque and posterior translation movements (16). Recent studies revealed that rotational movements were particularly under expressed with the posterior areas being especially affected and that the center of rotation of the tooth showed variation from the digital planification during rotation movements putting into evidence that crown-lead thermoplastic force systems are not always able to achieve the root control planned (22, 25). In the objective of bettering the accuracy and predictability of the teeth movements with clear aligners therapy, several systems have been developed. The careful selection and placement of attachments has been demonstrated to improve the accuracy of rotations, extrusions and mesiodistal translations requiring root control (26), the staging protocols implemented also have a great impact on the results as they influence tracking of the progress and expression of the movements, a conservative approach with longer time spent between changes of trays can improve the reliability of complex movements (6). An additional factor able to influence the effectiveness of the movements performed is the software and material used, both of which are dependent on the brand selected by the clinician, studies have shown that the choice of planning software can alter the predicted results of the treatment and that differences were apparent in the accuracy of the clinical result across different systems (15, 18).

1.3.3 Current limitations and clinical implications

Methodological issues have been put into evidence in current clear aligners research, small sample sizes in studies, heterogeneity across cases, inter-brand variations and lack of standardization protocols and metrics reporting the effectiveness, accuracy and predictability of each movement, pose a great challenge in the correct assessment of orthodontic movements with clear aligners (5, 14). Clinically the evidence has supported the use of over-corrections at the virtual planning stage to counteract the discrepancies in movements and reach the expected treatment outcome (15, 27), however as the indications of clear aligners therapy broaden a need for a tailored solution maintaining the predictability of the method arises as the systematic use of overcorrections can reduce the overall precision of the treatment (28).

2. OBJECTIVE

2.1 PICO question

In patients undergoing orthodontic treatment (P) with clear aligners therapy (I), how do digitally planned orthodontic tooth movements compare with clinically achieved movements (C) regarding treatment effectiveness (O)?

2.2 Objective

To evaluate the predictability of the different teeth movements with clear aligners (tipping, rotation, bodily movements, intrusion and extrusion) comparing between digital treatment plan teeth movements vs clinical teeth movement.

3. MATERIAL AND METHODS

3.1 Study design

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) in the objective of ensuring reproducibility, transparency and accuracy of the research. The aim was to evaluate the effectiveness of planned orthodontic movements in clear aligners therapy by comparing their accuracy and predictability with the orthodontic movements clinically achieved.

Studies were seen as eligible according to the PICO framework already established, they needed to include our population of interest meaning they studied patients undergoing orthodontic treatment with clear aligners, the intervention part considered that their treatment needed to have previously been digitally planned in the appropriate aligners' software. The study had to be comparing the planned and achieved effectiveness of the different types of movements intended either at the end of treatment or at a previously defined stage of it and needed to express their results using quantitative data and use it to compare the results planned with the ones achieved for the different types of orthodontic movements which are rotation, torque, tipping, translation, intrusion and extrusion.

3.2 Search strategy

The comprehensive literature research was performed to identify relevant studies was done using PubMed, Medline and the website of the library of the Universidad Europea, filtering out articles published more than 10 years ago, to ensure this review was based on recent findings based on studies using current aligner therapy technology.

The search strategy combined Medical Subject Headings (MeSH) with free-text terms to increase precision while keeping a broader outlook for all relevant publications related to clear aligners and orthodontic movements. The keywords used included terms such as "clear aligners", "Invisalign", "removable aligners" in order to describe the appliance used, "rotation", "extrusion", "intrusion", "translation", tipping" and "torque" were used as keywords describing the specific types of orthodontic movements studied and the terms performance related to the search regarding the effectiveness of the technique were "accuracy", "predictability" and "achieved movements".

All collected studies were uploaded in the reference management software Zotero, duplicates were removed, and selection of the studies was assessed in two phases, a first selection was made according to the title and abstract content and the if articles were seen as eligible after the first phase they went through a second selection during which a full text assessment was performed to determine if the study would finally be included in this review.

3.3 Eligibility criteria

The aim of this research is to compare the planned performance of clear aligners therapy with the clinical results achieved, and not to compare their performance with fixed appliances; therefore, studies comparing the performance of the two different methods were excluded from our selection. The articles considered were all clinical studies published in credible scientific publications, that were peer reviewed and presented no to minimal conflict of interest. The articles selected included prospective and retrospective clinical studies, controlled clinical trials and observational studies, while also excluding case reports, systematic reviews, or narrative reviews. Studies not reporting quantitative comparisons between the movements planned by the software and the movements clinically achieved during the trial were excluded and only articles written in English were selected.

3.4 Data extraction

Ensuing the previous selection, the relevant information was extracted from the articles reviewed by using a standardized data collecting system. The system used in this review aimed to gather comparable information from each study, facilitating the interpretation, comparison and synthesization of the results obtained in each case. The general information collected in each study encompassed the title, the name of the authors of the study, the type of study design, the sample size of patients studied. Technical information regarding the type of aligner system and digital software used, the type of tooth movements evaluated (rotation, translation, torque, tipping, extrusion, intrusion), the method used to measure treatment progress and outcome (superimposition or imaging techniques with CBCTs, intraoral scans or digital models overlay) were also recorded. Finally, findings regarding the quantitative comparisons made in each study, either through a quantitative discrepancy or a percentage of efficiency between the orthodontic movements planned and the one achieved during the treatment as well as any additional conclusions obtained through the study were collected. The information subsequently gathered was then systematically organized and entered in a data extraction table designed for this

review to ensure consistency in the comparison of variables and minimizing the risks of errors or omission, allowing an easier, more complete and reliable analysis of the data. By structuring the information in a structured table format, the identification of patterns and differences in the results obtained across studies was facilitated leading to a more comprehensive analysis of the effectiveness of orthodontic movements in clear aligner therapy.

3.5 Integration of study results

Due to heterogeneity across the different studies included in this reviewed, in most part due to a lack of standardization in the aligner system and software used, the type of movement observed, and the measuring method used, a meta-analysis cannot be performed, in its place the approach chosen was a narrative synthesis which involves a structured description of the quantitative findings allowing for a comprehensive interpretation of the evidence while keeping clarity in the areas where comparability was limited.

Across this process the average performance of treatment with clear aligners was highlighted as well as the variability shown across movement types, the clinical significance of the discrepancies encountered between the orthodontic movements planned and the ones clinically achieved was considered in relation to the treatment finishing quality. The evidence collected was then used to create the discussion part of the article and conclusions were subsequently obtained putting into evidence the clinical implications of the research.

4. RESULTS

4.1 PRISMA flowchart

The study selection process is summarized in the 2020 PRISMA flowchart (Figure 1), a total of 1128 articles were identified using PubMed, Medline and the website of the library of the Universidad Europea, after removal of the duplicates 976 records were screened based on abstract and title of which 918 were excluded. Following this step, 58 records were sought for retrieval with 7 of those unavailable. Later, 51 reports were assessed for full-text eligibility, and 36 were excluded in accordance with the previously stated criteria. Finally, 15 remaining articles were included in this review.

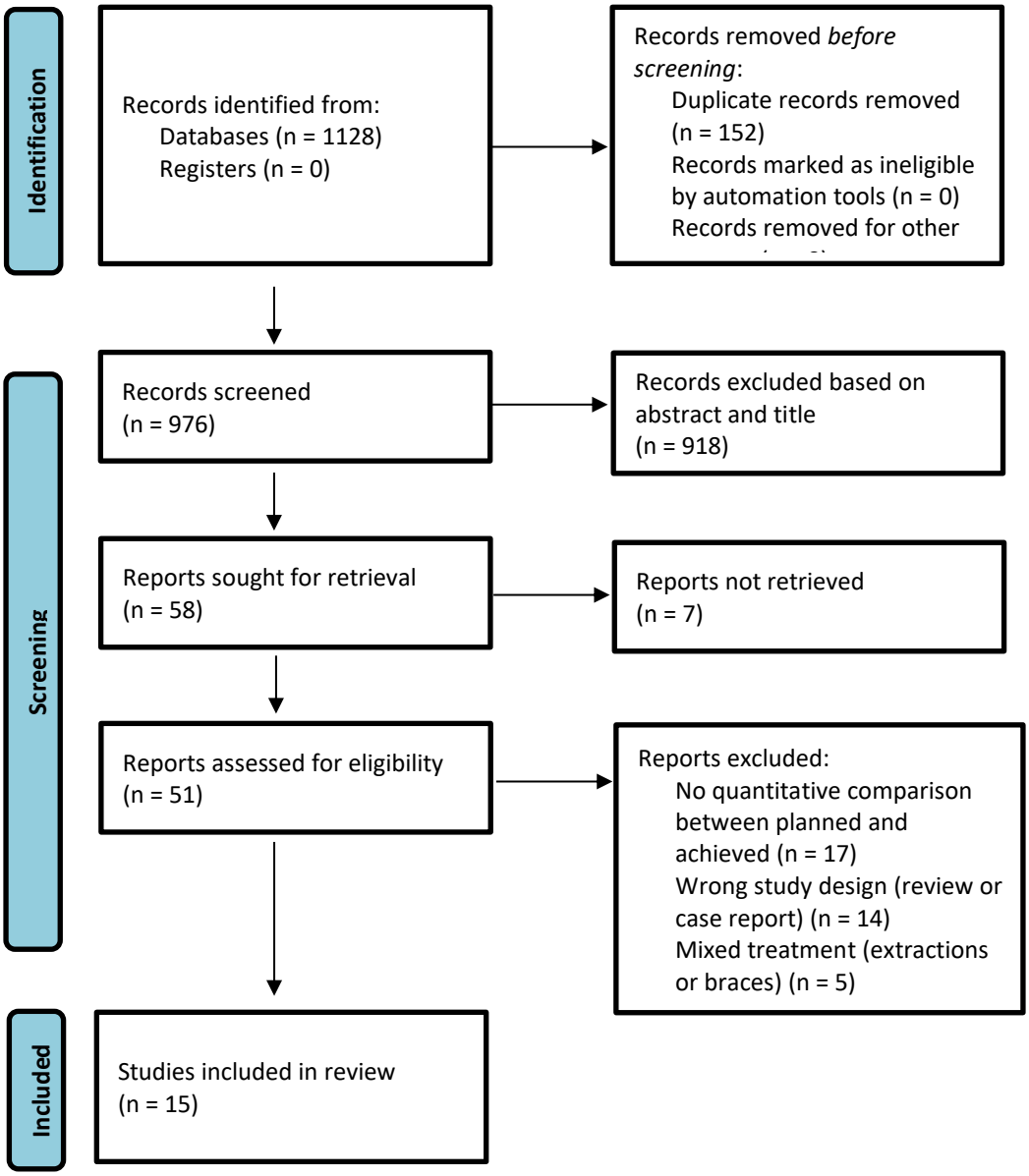


Figure 1. PRISMA Flowchart of the included reports in the study
Source : Page MJ, et al. BMJ 2021;372:n71. doi: 10.1136/bmj.n71.

4.2 Data extracted from the studies selected

Table 1: Characteristics of the studies included in this systematic review

Authors (year)	Study design	Sample size	Treatment duration	Aligner system	Digital planning software	Measuring method
Castroflorio et al. (2022)	Prospective observational study	79 patients	9.8 ± 3.8 months	Invisalign®	Clincheck®	Digital models and virtual ClinChecks
de-la-Rosa-Gay et al. (2025)	Retrospective cohort study	98 patients	8.17 ± 11.41 months	Invisalign®	Clincheck®	Digital scans and Clinchecks compared before 1st refinement
Suarez et al. (2025)	Prospective interventional study	100 patients (divided in 4 groups of 25)	≥15 aligners before refinement	Angel Aligners, Invisalign, Spark, HeySmile	Appropriate software according to brand: iOrtho, Clincheck, Approver, HeySmile	Digital scans and predicted models (software according to system used). Measured in Exocad
Al Samman et al. (2024)	Retrospective observational study	24 patients (divided in 2 groups of 12)	Group 1: 19.13 ± 6.24 months Group 2 : 17.16 ± 4.85 months	Invisalign®	Clincheck®	Digital scans and Clinchecks superimposed with eModel 9.0 "Compare" software
Bilello et al. (2022)	Prospective observational study	10 patients	21.2 aligners per arch before refinements on average	Invisalign®	Clincheck®	Digital casts as STL files and superimposed with Meshlab software.
Morales-Burruezo	Retrospective	114 patients	NR	Invisalign®	Clincheck®	Superimposition of

et al. (2020)	observational study					ClinCheck with RulerSwift for distances and angles
Riede et al. (2021)	Retrospective observational study	30 patients	NR	Invisalign®	Clincheck®	OnyxCeph 3D software used with OrthoCAD + ClinCheck contact comparisons
Groody et al. (2023)	Multicenter randomized controlled clinical trial	38 patients	22.6 ± 3.5 trays	Invisalign®	Clincheck®	Superimposition of iTero digital scans and ClinCheck with best fit algorithm
Yan et al. (2023)	Retrospective observational study	51 patients	NR	Invisalign®	Clincheck®	Superimposition of iTero digital scans and ClinCheck using Geomagic Studio 2014
Mamani et al. (2024)	Retrospective observational study	14 patients	49.14 ± 14.02 aligners	Invisalign®	Clincheck®	Cephalometric xrays taken with Orthopantomograph OP 200D printed and manually traced

Inchingolo et al. (2023)	Retrospective observational study	35 patients divided in 2 groups (A: 10 B:25)	Group A: 12 aligners Group B: 24 aligners	Nuvola®	Nuvola® simulation software	Digital caliper in Medit Design app used on digital scans
D'Antò et al. (2022)	Prospective interventional study	17 patients	Evaluated at stage 15 (after the 15th aligner set)	Airnivol®	Airnivol® internal planning software	Digital scans compared using VAM software, placing 72 reference points per arch
Grunheid et al. (2017)	Retrospective cohort study	30 patients	11 ± 4 months	Invisalign®	Clincheck®	Digital scans superimposed with ClinCheck predictions
Al-Nadawi et al. (2020)	Randomized clinical trial	75 patients	5-9 months according to aligner change schedule	Invisalign®	Clincheck®	iTero scans exported on ClinCheck Pro compared by best-fit 3D superimposition
Alswajy et al. (2023)	Retrospective observational study	206 patients	NR	Invisalign®	Clincheck®	iTero scans and ClinCheck outcome simulator

Summary of the characteristics of the studies included in this review. All included studies are in accordance with the eligibility criteria defined, in total 15 studies were considered with various design types included such as prospective observational studies, randomized clinical trials and retrospective cohort studies. Sample sizes of the studies included ranges from 10 to 206 patients, and while several system types were included most studies evaluated the effectiveness of aligners from the Invisalign brand system. Various measurement methods were used in the different studies to compare achieved and predicted movements, particularly superimposition

of digital STL files acquired through intraoral scanning. Variations of brand and measuring methods highlight the heterogeneity observed across studies.

Table 2: Quantitative accuracy of aligners by tooth movement type

Authors (year)	Movement type	Planned amount of movement	Achieved amount of movement	Discrepancy planned/ achieved	Overview of the results
Castroflorio et al. (2022)	Tipping (mesio-distal) Torque (bucco-lingual) Rotation Translation (mesio-distal, bucco-lingual, vetical)	Maxillary average: Tipping = 2.66° Torque = 3.14° Rotation = 6.91° Mesio-distal translation = 0.60 mm Bucco-lingual translation = 0.78 mm Vertical translation = 0.49 mm Mandibular average: Tipping = 3.09° Torque = 2.43° Rotation = 7.78° Mesio-distal translation = 0.38 mm Bucco-lingual translation = 0.83 mm Vertical translation = 0.75 mm	NR	Maxillary average discrepancy: Tipping = 2.45° Torque = 3.83° Rotation = 2.92° Mesio-distal translation = 0.26 mm Bucco-lingual translation = 0.22 mm Vertical translation = 0.35 mm Mandibular average discrepancy: Tipping = 2.59° Torque = 2.99° Rotation = 2.67° Mesio-distal translation = 0.35 mm Bucco-lingual translation = 0.28 mm Vertical translation = 0.41 mm	Almost all movements were under-achieved.
de-la-Rosa-Gay et al. (2025)	Transverse expansion (arch width change	Average maxillary expansion planned in	Average maxillary expansion achieved across all	Average maxillary discrepancy= 1,2mm	In cases of transverse expansion cases, clear aligners are

		the arch= 3,1mm Average mandibular expansion planned in the arch= 1,9mm	teeth in the arch = 1,89mm Average mandibular expansion across all teeth in the arch= 1,74mm	Average mandibular discrepancy= 0,625mm	less reliable the larger the correction needed
Suarez et al. (2025)	Dentoalveolar expansion (measure of inter-teeth distance)	Average planned movement (measured as increase in distance between 13-23): Overall = 2.78 mm **By brand:** -Invisalign = 2.80 mm -Spark= 2.26 mm -Angel= 2.66 mm -HeySmile= 3.39 mm	Average achieved movement (measured as increase in distance between 13-23): Overall= 1.42 mm **By brand:** -Invisalign = 1.10 mm -Spark= 1.20 mm -Angel= 1.52 mm -HeySmile= 1.84 mm	Overall discrepancy= 1.36mm **By brand:** -Invisalign = 1.70 mm -Spark= 1.06 mm -Angel= 1.14 mm -HeySmile= 1.55 mm	Significant differences are observed between achieved and planned movements, the overall most predictable brand was Angel and the least predictable was Invisalign.
Al Samman et al. (2024)	Torque (labio-lingual inclination)	Mean planned torque in Power Ridge group= 11.91° Mean planned torque in attachment group= 10.21°	Mean achieved torque in Power Ridge group= 7.81° Mean achieved torque in attachment group= 7.25°	Discrepancy in Power Ridge group = 4.51° Discrepancy in attachment group= 3.74°	The predicted labiolabial torque movements are underachieved in both groups with no significant difference between them.
Bilello et al. (2022)	Rotation Intrusion Tipping (vestibulo-lingual)	NR	NR	Results of this study were expressed as percentage of the accuracy of the clinical	This study supports that careful treatment planning, the use of auxiliary elements and

				movement compared to the predicted one. Rotation: Mean= 86,1% Range= 70.4% (mandibular first premolars) - 96.1% (maxillary central incisors*)* Intrusion: Mean= 92% Range= 86.7% (mandibular canines) - 98% (mandibular central incisors) Tipping: Mean= 93.1% Range= 80.7% (maxillary central incisors) - 97.5% (mandibular central incisors)	refinements allow a successful clinical expression of the planned results.
Morales-Burruezo et al. (2020)	Transverse expansion Molar inclination Molar rotation	NR	Transverse expansion: Canine= 1.87 ± 1.78 mm 1st premolar= 3.14 ± 2.25 mm 2nd premolar= 3.45 ± 2.09 mm	Transverse expansion: Canine= 0.63 ± 0.75 mm 1st premolar= 0.77 ± 1.44 mm 2nd premolar= 0.81 ± 1.26 mm	Aligners are effective for transverse expansion, especially premolars. Predictability is moderate. Overcorrection should be considered

			1st molar= 2.57 ± 1.83 mm 2nd molar= 0.45 ± 1.83 mm Inclination: 1st molar= 2.19 ± 4.42 mm Rotation: 1st molar= 2.34 ± 4.06 mm	1st molar= 0.69 ± 1.21 mm 2nd molar= 0.25 ± 1.97 mm Inclination: 1st molar= -0.65 ± 3.04 mm Rotation: 1st molar= 0.10 ± 3.31 mm	
Riede et al. (2021)	Molar rotation Molar inclination Transverse width changes	Molar rotation = 3.43° Arch expansion = 2.13 mm Molar inclination = 4.53°	Molar rotation = 3.17° Arch expansion = 2.00 mm Molar inclination = 3.33°	Molar rotation discrepancy = 3.03° Arch expansion discrepancy = 0.48 mm Molar inclination discrepancy = 3.50°	SmartTrack does not significantly improve transverse predictability. Greater planned expansion = lower effectiveness. Overcorrection may be necessary.
Groody et al. (2023)	Extrusion of maxillary lateral incisors	Average planned extrusion= 0.84 mm	Average achieved extrusion= 0.63 mm	Average discrepancy of extrusion= 0.21 mm	Extrusion remains partially predictable. Horizontal attachments improve efficiency.
Yan et al. (2023)	Tipping Intrusion Bodily movements (labial direction)	Tipping (proclination) = 13.9 ± 7.3° Intrusion= 1.5 ± 1.1 mm Translation= 0.6 ± 2.2 mm	Tipping (proclination) = 9.7 ± 7.3° Intrusion= 0.8 ± 1.1 mm Translation= 1.3 ± 1.5 mm	Tipping (proclination) = 4.2 ± 4.5° Intrusion= 0.7 ± 1.1 mm Translation= − 0.7 ± 1.5 mm	Controlled root movement is limited. Intrusion predictability is low. Overtreatment is required. Excessive labial crown

					movement may occur.
Mamani et al. (2024)	Bodily translation (mesio-distal) Tipping (mesio-distal)	Translation= 2.33mm Tipping= 1.01°	Translation= 0.89mm Tipping= 1.30°	Translation= 1.45mm Tipping= -0.29°	Translation is significantly under-achieved. Tipping control acceptable. Distalization efficiency is low in first aligner series.
Inchingolo et al. (2023)	Transverse expansion Dental tipping	Group A: Tip: C=1.2 ± 1.7 mm 1st PM= 2.5 ± 1.8 mm 2nd PM= 3.1 ± 1.8 mm 1st M= 1.8 ± 1.8mm Gingival: C=1.1 ± 1.7 mm 1st PM= 2.5 ± 1.3 mm 2nd PM= 2.8 ± 1.3mm 1st M=2.4 ±1mm Group B: Tip: C= 1.3 ± 1.8mm 1st PM= 3.5 ± 2.2mm 2nd PM= 4.2 ± 2.6mm 1st M= 1.8 ± 1.6mm Gingival: C= 2.1 ± 3mm 1st PM= 3 ± 1.9mm	Group A: Tip: C= 1.1 ±1.5mm 1st PM= 2.2 ± 1.4mm 2nd PM= 2.5 ± 1.3mm 1st M= 1.4 ± 1.9mm Gingival: C= 0.5 ± 1.1mm 1st PM= 1.5 ± 1.1mm 2nd PM= 1.6 ± 0.9mm 1st M= 1.4 ± 0.7mm Group B: Tip: C= 1.1 ± 2mm 1st PM= 2.8 ± 1.8mm 2nd PM= 3.6 ± 2.4mm 1st M= 2.8 ± 2mm Gingival: C= 0.9 ± 1.4mm 1st PM= 2.1 ± 1.3mm	Group A: Tip: C= 0.22 ± 0.8mm 1st PM= 0.3 ± 0.6mm 2nd PM= 0.55 ± 0.8mm 1st M= 0.4 ± 2.8mm Gingival: C= 0.58 ± 1.1mm 1st PM= 1 ± 0.8mm 2nd PM= 1.13 ± 0.9mm 1st M= 0.93 ± 0.7mm Group B: Tip: C= 0.18 ± 1.39mm 1st PM= 0.75 ± 1.33mm 2nd PM= 0.57 ± 1.61mm 1st M= 0.83 ± 1.52mm Gingival: C= 1.18 ± 2.82mm 1st PM= 0.84 ± 1.19mm	Transverse expansion mainly achieved via tipping, not bodily expansion.

		2nd PM= 3.6 ± 2.1mm 1st M= 3.4 ± 2.5mm	2nd PM= 2.2 ± 1.4mm 1st M= 1.6 ± 1.1mm	2nd PM= 1.42 ± 1.57mm 1st M= 1.79 ± 2.15mm	
D'Antò et al. (2022)	Torque (bucco-lingual angulation) Tipping (mesio-distal angulation) Rotation	Mean planned torque movement= 2.8° Mean planned tipping movement= 3.4° Mean planned rotation movement= 3.8°	Mean achieved torque movement= 2.8° Mean achieved tipping movement= 3.5° Mean achieved rotation movement= 3.9°	Discrepancy torque movements= 0° Discrepancy tipping movements= -0.1° Discrepancy rotation movements= -0.1 °	No significant overall difference observed between planned and achieved movements. Heterogeneity in accuracy across movements.
Grunheid et al. (2017)	Translation (mesio-distal, vestibulo-lingual) Vertical movements (intrusion/ extrusion) Tipping Torque Rotation	NR	NR	Only the discrepancy between predicted and achieved tooth position was provided: Average discrepancy planned/ achieved in maxillary arch: Translation= 0.14mm Rotation= 1.12° Tipping= 0.51° Torque= 0.43° Average discrepancy planned/ achieved in mandibular arch:	Invisalign provides satisfactory results, clinicians need to be aware of likely underexpression of rotation, torque and arch expansion.

				Translation= 0.09 mm Rotation= 0.83° Tipping= 0.49° Torque= 0.81°	
Al-Nadawi et al. (2020)	Translation (mesio-distal, vestibulo-lingual) Vertical movements (intrusion/ extrusion) Tipping Torque Rotation	NR	NR	Only the discrepancy between planned and achieved in each group was shared: 7-Day Protocol Translation = 0.28 mm Vertical = 0.38 mm Tip = 3.28° Torque = 3.05° Rotation = 2.76° 10-Day Protocol Translation = 0.26 mm Vertical = 0.36 mm Tip = 3.04° Torque = 2.96° Rotation = 2.83° 14-Day Protocol Translation = 0.24 mm Vertical = 0.33 mm Tip = 2.66° Torque = 2.40° Rotation = 2.46°	7-day protocol presents similar results to the 14 days protocol while shortening treatment time, occasional 14 days wear should be considered when performing more challenging posterior movements (torque, tip, rotation).

Alswajy et al. (2023)	No individual movement but treatment parameters (overjet, overbite, intercanine/ intermolar width, crowding, interincisal angle)	Overjet= 2.57 ± 0.72 mm Interincisal angle= 129.4 ± 7.62 ° Overbite= 1.66 ± 0.71 mm Upper Intercanine Width = 36.81 ± 2.01 mm Lower Intercanine Width = 28.21 ± 1.58 mm Upper Intermolar Width = 55.81 ± 2.89 mm Lower Intermolar Width = 51.59 ± 2.92 mm	Overjet= 2.77 ± 1.11 mm Interincisal angle= 131.96 ± 9.59° Overbite= 2.44 ± 1.46 mm Upper Intercanine Width = 36.26 ± 2.21 mm Lower Intercanine Width = 27.99 ± 1.64 mm Upper Intermolar Width = 54.86 ± 3.16 mm Lower Intermolar Width = 51.10 ± 3.19 mm	Overjet= 0.20 ± 1.11 mm Interincisal angle= 2.56 ± 6.16° Overbite= 0.77 ± 1.29 mm Upper Intercanine Width = 0.53 ± 1.05 mm Lower Intercanine Width = 0.53 ± 1.05 mm Upper Intermolar Width = 0.95 ± 2.05 mm Lower Intermolar Width = 0.49 ± 2.08 mm	Overall ClinCheck presents satisfactory accuracy, system providers might need to amplify movements in the software to decrease refinement needs.

Synthetizes the movement in each of the studies and presents a quantitative comparison of the orthodontic movements planned and the ones achieved using clear aligner therapy. The different types of movements evaluated were torque, tipping, rotation, bodily translations (mesio-distal and bucco-lingual directions), vertical movements (both intrusion and extrusion) as well as transvers expansion of the arch. Majority of the studies put in evidence a difference between the amount of movement planned and the amount that was achieved with a general conclusion towards underexpression of the different movements. Translations, torque and expansion movements showed on average the highest amount of discrepancy across studies with its extent being dependent on the tooth position and amount of movement performed.

Table 3: Accuracy by movement type synthesis

Movement type	Number of studies contributing	Accuracy range	Conclusion
Tipping	8 studies	20.7-102.9% Lowest: Castroflorio et al. Highest: D'Antò et al.	Tipping is in general one of the most predictable type of movements. Most studies report a high accuracy, however underexpression of the movement can occur depending on the tooth type and movement magnitude required.
Torque	7 studies	37.5-100% Lowest: Castroflorio et al. Highest: D'Antò et al.	Torque shows variable predictability. Several studies report underexpression and clinically significant discrepancies, others show a great accuracy of the movement.
Vertical (intrusion/ extrusion)	6 studies	Intrusion: 53.3-92% Lowest: Yan et al. Highest: Bilello et al. Extrusion: 73% Groody et al.	Intrusion appears moderately to highly predictable in some groups, whereas extrusion shows a lower accuracy. Control of vertical movements remains one of the least consistent variables across teeth movements.
Rotation	7 studies	41.2-102.6% Lowest: Castroflorio et al. Highest: D'Antò et al.	Rotation accuracy is highly dependent on the tooth studied and the degree of rotation required, showing very variable results. Larger prescribed movements tend to show higher underexpression.
Translation (mesio-distal and bucco-lingual)	5 studies	Mesio-distal: 37.75-41.7% Lowest: Mamani et al. Highest: Castroflorio et al. Bucco-lingual: 55.3-69.2% Lowest: Inchingolo et al. Highest: Castroflorio et al.	Translation movements, particularly distalization of posterior teeth are very unpredictable. A significant underexpression of mesio-distal movement is consistently reported. Bucco-lingual movements are generally more predictable.
Arch expansion (transverse)	5 studies	45-76.1% Lowest: Riede et al. Highest: Morales-Burruezo et al.	Transverse expansion movements are moderately predictable, with some tooth types presenting higher accuracy than others. It is also important to note a reduced predictability when planning a greater expansion.

Synthesis of the accuracy of each orthodontic movement type reports in the included studies. The number of included studies evaluating each type of movement, band the range of accuracy found among the studies were summarized. The orthodontic movement showing the overall highest predictability was tipping, while mesio-distal bodily translations and extrusions demonstrated the lowest accuracy. Other movements such as torque and rotation showed more heterogenous results that were highly dependent on the magnitude of movement and the tooth studied.

5. DISCUSSION

5.1 General predictability of clear aligner therapy

Overall, this review demonstrated that most orthodontic movements can be achieved through clear aligners therapy which provided moderately accurate results, although with discrepancies persisting when comparing the orthodontic movements digitally planned and the ones clinically achieved.

Across most of the studies reviewed, orthodontic movements tended towards an underexpression of the digital plan in a clinical setting, which aligns with the current consensus in the literature, as seen in a similar systematic review published in 2019 showing that clear aligners therapy shows some level of efficiency but still presents biomechanics limitations (37). These findings align to support the idea that digital treatment plan simulation software overestimate the magnitude of the movements expressed during the treatment, putting into evidence the critical need for practitioners to be aware of the biomechanical limitations, and take them into account when planning treatments.

5.2 Differences in predictability according to the type of orthodontic movement

While studying the different types of orthodontic movements, some appeared more reliable than others. Tipping consistently was considered one of the most predictable types of movements with several of the studies (24, 31) reporting a consistent high accuracy and was seen as very reliable when planning movements of a limiting amplitude. Quantitative findings, such as those reported by Bilello et al., showed mean accuracy values exceeding 90% (24), while Castroflorio et al. reported relatively small discrepancies between planned and achieved tipping movements (4). This is explained by the simpler forces systems required for tipping movements which are mainly crown based and can easily be delivered through the clear aligner system.

However, other orthodontic movements such as rotations showed lower predictability with a great variability in accuracy depending on the study analyzed and other factors such as amount of movement required and tooth position (4, 28, 34). For example, Bilello et al. reported a wide range of accuracy values, from approximately 70% in mandibular premolars to over 90% in maxillary incisors (24), highlighting the variability of outcomes. Similarly, Riede et al. observed

discrepancies between planned and achieved molar rotations, indicating reduced effectiveness in posterior teeth (28).

The predictability of vertical movements also showed inconsistencies with intrusive movements presenting a moderate to high accuracy and extrusive orthodontic only demonstrating limited results with Groody et al. reported only partial expression of planned extrusion movements (29). On the other hand, Bilello et al. reported a high accuracy of intrusive movement with up to 98% accurate intrusive movement of mandibular central incisors (24), and Yan et al. highlighted a limited predictability of vertical control, especially when performing more complex movements (30). These findings put in evidence the remaining challenges orthodontists are faced with when delivering precise vertical forces with aligners.

Additionally, the results found regarding torque movements showed a great variability with some studies showing adequate reliability while others demonstrated important discrepancies between the movement planned and achieved. Al Samman et al. quantitatively demonstrated discrepancies of approximately 3–4° between planned and achieved torque movements, regardless of the biomechanical approach used (19), whereas D'Antò et al. reported no differences between the overall amount of torque movement prescribed and achieved (33).

Bodily translations movements, particularly mesio-distal movements and distalization of posterior teeth were generally considered some of the least predictable movements with a significant underexpression of the movement reported across multiple studies (31, 34, 35). Mamani et al. found that a planned translation of 2.33 mm resulted in only 0.89 mm of clinically achieved movement in mesio-distal translations (31), while Castroflorio et al. also reported reduced accuracy in translation movements across both arches (4).

Transverse expansions were predictable with their effectiveness varying depending on the magnitude of the expansion planned. Riede et al. states that a greater expansion provides a lower predictability of movement (28), while other studies such as de-la-Rosa-Gay et al. and Suarez et al. reported significant discrepancies between planned and achieved expansion, with up to 1.7mm difference between the planned and achieved expansion (15, 18).

In summary, the findings recorded here indicate that the effectiveness of orthodontic movements with clear aligners is highly dependent on the type of movement performed.

5.3 Limitations of complex movements with aligners

The orthodontic movements associated with less predictability were those requiring a greater amount of biomechanical control and were often linked to the need for root movement.

Significant discrepancies were reported in the expression of torque movements in several studies with torque movements evaluated by Al Samman et al. and D'Antò et al. revealing discrepancies of several degrees between planned and achieved angulation (19, 33), demonstrating the difficulties faced with root control when performing clear aligners therapy due to the forces being primarily applied at the level of the crown (30).

Likewise, bodily translation movements present difficulties associated with the need for the force applied to be balanced across the root and crown to prevent unwanted and uncontrolled tipping of the tooth. In several cases (30, 31), aligners have been shown to produce tipping when the treatment plan was aiming for a translation movement due to unproper biomechanical control of the appliance.

Similar cases have been seen when trying to produce transverse arch expansion with clear aligners, which showed moderate predictability, where authors such as Morales-Burruezo et al. and Inchingolo et al. reporting that the final expansion achieved was frequently due to dental tipping rather than to true expansion of the arch, showcasing the difficulties of aligners in consistently producing controlled and complex root movements (27, 32).

5.4 Factors influencing the effectiveness of aligner treatment

Several factors influence the accuracy of the orthodontic movements performed with clear aligners; the magnitude of the movement required is one of them with accuracy decreasing as the amount of movement performed increases as observed in transverse expansion studies by Suarez et al. and Riede et al. (18, 28).

Another element influencing the results is the position of the tooth on which the movement is performed in the arch with posterior teeth demonstrating lower predictability than anterior teeth (35). The use of attachments can also be an important factor in the accurate expression of more complex movements as they heighten aligner retention and ensure a more precise force application. Movements such as torque, rotation or extrusion which largely go underexpressed without them as stated by Groody et al. their use improves the predictability of the treatment (29). These factors are closely related to the biomechanical limits clear aligners are faced with as they deliver intermittent forces highly dependent on the material and fit of the tray as well as on the compliance of the patient, resulting in less controlled forces and a reduced precision in complex movements (38).

It is essential for clinicians to that the digital models obtained at the start of the treatment are a digital predictive model of what could be achieved and not a guaranteed clinical outcome, they

do not consider biological variations, material limitations or patient related factors which can all impact the results (4). In addition, these factors should not be considered independently, as their interactions can significantly influence treatment outcomes. For instance, the combination of complex movements and poor patient compliance may substantially reduce treatment predictability. Moreover, strategies such as overcorrection to counteract the underexpression of certain movements, the use of attachments, and the addition of refinement stages to the treatment plan are all strategies that should be considered when creating a treatment plan for the clinician to achieve the best possible clinical outcome (24, 27-29).

These findings emphasize the need for careful case selection and treatment planning, considering the needs of the patient as well as the limitations of clear aligners.

5.5 Limitations of the review and future research direction

Several limitations are to be considered when interpreting the findings of this review, the studies reviewed presented an important heterogeneity with regards to the use of different aligners system and software, different measuring techniques and inconsistent outcome reporting methods. Different studies expressed their accuracy results in varied ways when using different metrics like millimeters, angular measurements or only reporting accuracy percentages, which makes a direct and precise comparison of results greatly complicated. Additionally, most of the studies evaluated were retrospective or observational which introduces the possibility of inaccuracies or bias among these articles. Moreover, the lack of a standardized measuring technique restricts the prospects of conducting a quantitative meta-analysis, requiring the results to be expressed narratively. Future research should strive to create standardized measurement protocols and include more prospective and randomized clinical trials to evaluate the effectiveness of aligner systems, attachment designs, and different treatment protocols. A more complete comprehension of these elements can better the accuracy of orthodontic movements and optimize treatment planning in clear aligner therapy.

6. CONCLUSIONS

Orthodontic movements executed with clear aligner therapy demonstrate a moderate overall effectiveness.

Clinically, clear aligners can be considered a predictable option for orthodontic movements, but careful case selection and biomechanical planning remain essential to achieve optimal results.

The predictability of orthodontic movements was highly dependent on the type of movement performed.

- Tipping consistently is the most accurate and reliable movement
- Rotation and torque demonstrate variability and a less consistent accuracy,
- Vertical movements are poorly predicted especially extrusion
- Bodily movements can be considered some of the least accurate especially when moving the teeth in the mesiodistal direction.
- Transverse expansion of the arch is seen as moderately predictable; however, they most often occur due to tipping of the tooth rather than through actual bodily displacement.

The magnitude of the orthodontic movement planned has a great impact on the results with bigger displacements showing less predictability, they were also affected by the complexity of the movement performed and the compliance of the patient with the removable appliance.

To compensate these limitations, dentists should include in their treatment planning overcorrection measures, the use of attachments and auxiliaries, as well as the implementation of refinement stages in later phases of the treatment.

The current literature shows significant heterogeneity in study design, measurement methods, and reporting, limiting direct comparison and preventing meta-analysis.

To improve the reliability and comparability of future research, it should focus on creating standardized measurement protocols and high-quality prospective studies.

7. SUSTAINABILITY

Clear aligner therapy presents both advantages and limitations when analyzed from a sustainability perspective.

From an environmental perspective, the use of clear aligners involves the production of multiple thermoplastic appliances throughout treatment which contribute to an increase in single-use plastic waste.

This raises concerns regarding resource consumption and waste management in dental practices. That is why improvements in the efficiency of clear aligner appliances are essentials as they could allow a reduction of the number of phases and trays required in each case limiting this waste.

Additionally, the digital workflow associated with clear aligner therapy reduces the need for conventional materials such as alginate impressions and plaster models, potentially decreasing material waste in other stages of treatment while also improving clinical efficiency and reducing char time.

Overall, while clear aligner therapy offers clear clinical and social advantages, developments in biodegradable materials and more efficient treatment protocols are necessary to improve its sustainability within dental practices.

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