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Review Article **Orthodontics**

Predictability of Tooth Rotational Movements with Clear Aligners: A Systematic Review of the Literature

Mohamed Amine Blouza[1*], Raslen Ghazel[2], Yesmine Abid[3], Wiem Ben Amor[4], Ines Dallel[5], Samir Tobji[6], Adel Ben Amor[7]

[1]Resident, University of Monastir, Faculty of Dental Medicine, Dento-Facial Orthopedics Department of Monastir Dental Clinic, Laboratory of Oral Health and Orofacial Rehabilitation, Tunisia
[2]Resident, University of Monastir, Faculty of Dental Medicine, Dento-Facial Orthopedics Department of Monastir Dental Clinic, Laboratory of Oral Health and Orofacial Rehabilitation, Tunisia
[3]Resident, University of Monastir, Faculty of Dental Medicine, Dento-Facial Orthopedics Department of Monastir Dental Clinic, Laboratory of Oral Health and Orofacial Rehabilitation, Tunisia
[4]Assistant Professor, University of Monastir, Faculty of Dental Medicine, Dento-Facial Orthopedics Department of Monastir Dental Clinic, Laboratory of Oral Health and Orofacial Rehabilitation, Tunisia
[5]Professor, PHD, University of Monastir, Faculty of Dental Medicine, Dento-Facial Orthopedics Department of Monastir Dental Clinic, Laboratory of Oral Health and Orofacial Rehabilitation, Tunisia
[6]Professor, PHD, University of Monastir, Faculty of Dental Medicine, Dento-Facial Orthopedics Department of Monastir Dental Clinic, Laboratory of Oral Health and Orofacial Rehabilitation, Tunisia
[7]Head of Dento-Facial Orthopedics Department of Monastir Dental Clinic, Faculty of Dental Medicine, Dento-Facial Orthopedics Department of Monastir Dental Clinic, Laboratory of Oral Health and Orofacial Rehabilitation, Tunisia

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***Corresponding author:** Mohamed Amine Blouza
Resident, University of Monastir, Faculty of Dental Medicine, Dento-Facial Orthopedics Department of Monastir Dental Clinic, Laboratory of Oral Health and Orofacial Rehabilitation, Tunisia

Abstract

Introduction: Clear aligners, introduced in the 1990s with the Invisalign® system, have transformed orthodontics by providing an esthetic and comfortable alternative to fixed appliances. However, questions remain regarding their effectiveness and predictability in achieving different tooth movements and specifically tooth rotation. This systematic review aimed to critically evaluate the efficiency of aligners in controlling rotational movements and to identify the factors influencing their predictability. ***Materials and Methods:*** A systematic review was conducted following the PRISMA guidelines. Electronic searches were performed in PubMed, Cochrane Library, and ScienceDirect using a PICOS-based strategy. Methodological quality and risk of bias were assessed using standardized tools (AMSTAR 2, NHLBI/NIH). ***Results:*** Studies published between 2014 and 2024 were included. After screening, 14 studies met the eligibility criteria, including prospective and retrospective cohort studies, and systematic reviews. The review revealed that accuracy of tooth rotation is moderate (≈37–60%), it can be improved with attachments and interproximal reduction, but decreases with large or rapidly staged movements. Despite some progress, rotational control remains a key clinical limitation requiring cautious planning and monitoring. ***Conclusion:*** Rotations with clear aligners are poorly predictable, particularly for canines and premolars due to limited aligner grip on rounded crowns which often requires the use of auxiliaries and overcorrection strategies. Future high-quality randomized clinical trials and standardized protocols are necessary to strengthen the evidence and improve clinical outcomes.

Keywords: Orthodontics; Invisible orthodontics; Clear aligners; Predictability.

INTRODUCTION

Clear aligners, introduced in the late 1990s with the Invisalign® system, have substantially transformed orthodontic practice by providing an aesthetic, comfortable, and removable alternative to fixed appliances. Their widespread adoption, particularly among adults, is mainly attributed to their transparency, discretion, and facilitation of oral hygiene.

Despite these advantages, the effectiveness and predictability of clear aligners—especially for complex movements such as rotations—remain debated. Unlike

fixed appliances that deliver continuous, multi-point forces, aligners rely on intermittent forces generated by thermoformed materials, resulting in variable biomechanical control. Predictability is influenced by multiple factors, including patient compliance, aligner material properties, attachment design, use of auxiliaries, and the accuracy of digital treatment planning.

As demand for aesthetic orthodontic solutions continues to increase, evaluating the scientific evidence on aligner performance is essential. Accordingly, this systematic review aims to assess the effectiveness of clear aligners in controlling the movement of rotation and to highlight key factors influencing it's predictability.

1. MATERIALS AND METHODS

We carried out this systematic review of the literature according to the criteria published by the international PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analysis) recommendations. Ethical approval for carrying out the study was given by the "Thesis Committee" of the Faculty of Dental Medicine of Monastir in March 2024.

1.1 Objective of the Study:

The purpose of this review was to answer the following question:

- In patients with dental malocclusion, does orthodontic treatment with aligners, compared to the planned virtual set-up model, yield predictable results in terms of rotational movements?

1.2 Eligibility Criteria:

The PICOS (population, intervention, comparison, outcome, study design) format was used to formulate the clinical question with defined inclusion and exclusion criteria (Table 1). All articles included in this systematic review met the following criteria:

Table 1: Eligibility criteria

Domains	Inclusion Criteria	Exclusion Criteria
Participants	Humans with permanent dentition	Children, Animals, In vitro study, Computer simulations
Intervention	Orthodontic treatment with clear aligners using aligner-specific auxiliaries.	Orthodontic treatment with appliances other than aligners and/or using auxiliaries not associated with aligners (Mini-screws, palate expander, elastics...).
Comparaison	The virtual model built using simulation software, representing the ideal outcome.	Absence of data from the virtual setup model
Outcome	The amount of rotational movements achieved versus those programmed (in mm or degrees) and their degree of precision. Factors influencing the predictability of rotation (use of attachments, wear time, materials, etc.).	Other results.
Study design	Systematic review (with or without meta-analysis), Randomized or non-randomized controlled trial, Cohort study (retrospective or prospective)	Non-original article, Narrative review, Letter to the editor, Case report, Case series, Expert opinion

1.3 Information Sources and Search:

Two reviewers independently conducted a comprehensive search using a combination of controlled vocabulary (MeSH) and free text terms. PubMed, Cochrane Library and ScienceDirect were searched from January 2014 to august 2024 (period of ten years). Other than publication date, the search restrictions included only English and French articles as well as full text and references availability. MeSH keywords were selected and combined with Boolean operators AND/OR to obtain the following search equation used on the different electronic databases:
orthodontic* AND (clear aligners OR aligners) AND (predictability OR efficiency OR efficacy) AND tooth movement

1.4 Study Selection:

The process of selecting studies was conducted independently and in duplicate. All pertinent articles were imported into Zotero, a bibliography generator. Initially, duplicate articles were eliminated. Subsequently, titles and abstracts were scrutinized for eligibility. Full-text reports were consulted for articles that appeared to meet the inclusion criteria. Ultimately, relevant articles were subject to comprehensive analysis. Disagreements regarding inclusion were resolved by discussion between the two authors.

1.5 Data Collection Process and Items:

Data from the chosen articles for this study were extracted using a predefined standardized form by two independent reviewers. The collected information included author, year, number of participants, intervention, outcomes, and author conclusions. In cases of doubt or disagreement between the two reviewers, resolution was achieved through discussion.

1.6 Risk of Bias of Individual Studies:

The assessment of the risk of bias (RoB) of the included studies was performed by several tools depending on the type of each study:

*** The AMSTAR 2 test:**

(AMSTAR revised), was used to assess the quality of systematic reviews, as well as the search strategy, presentation of results, bias, sources of conflicts of interest and funding and the bias of the authors. This assessment grid was found to be reliable, valid, precise and easy to use [1]. It consists of a series of 16 questions with 3 possible answers: "Yes", "Partial yes" and "No". If the systematic review is not accompanied by a meta-analysis, then we write "No meta-analysis". For the calculation of the total score, one point is assigned to each "Yes" response, half a point is assigned to each "Partial Yes" response, and no points are assigned to the "No" and "No meta-analysis" responses. For each study, the number of points obtained is transformed into a grade A, B or C, according to the protocol described below:

- Grade A: 11 to 16 points out of 16: high quality study.
- Grade B: 7 to 10 points out of 16: study of average quality.
- Grade C: 0 to 6 points out of 16: low quality study.

*** The NHLBI, NIH quality assessment tool:**

this is a tool developed by the NIH (National Institutes of Health) [2] and used in our review to assess the methodological quality of cohort studies and case-control studies with control group. Each type of study has a very specific scale to assess its risk of bias. For cohort studies, the scale is made up of 14 questions to which 3 answers are possible: "Yes", "No" or "Unsure". A "yes" response indicates that the criterion is met and a point is thus awarded. For the answers "No" and "Unsure" no points are awarded. The total score is calculated as follows:

- High quality study: 12 to 14 points out of 14.
- Average quality study: 8 to 11 points out of 14.
- Low quality study: 0 to 7 points out of 14.

2. RESULTS

3.1 Study Selection:

The results of the electronic search and the subsequent article selection process were visualized in the PRISMA flow diagram, aligning with PRISMA guidelines. Initially, 1299 studies were identified through both database and manual searches. Following the elimination of duplicates, 1245 studies persisted, and only 43 advanced beyond the stage of title and abstract screening. Ultimately, 14 articles were included in the final selection, as depicted in the PRISMA flow diagram (Figure 1).

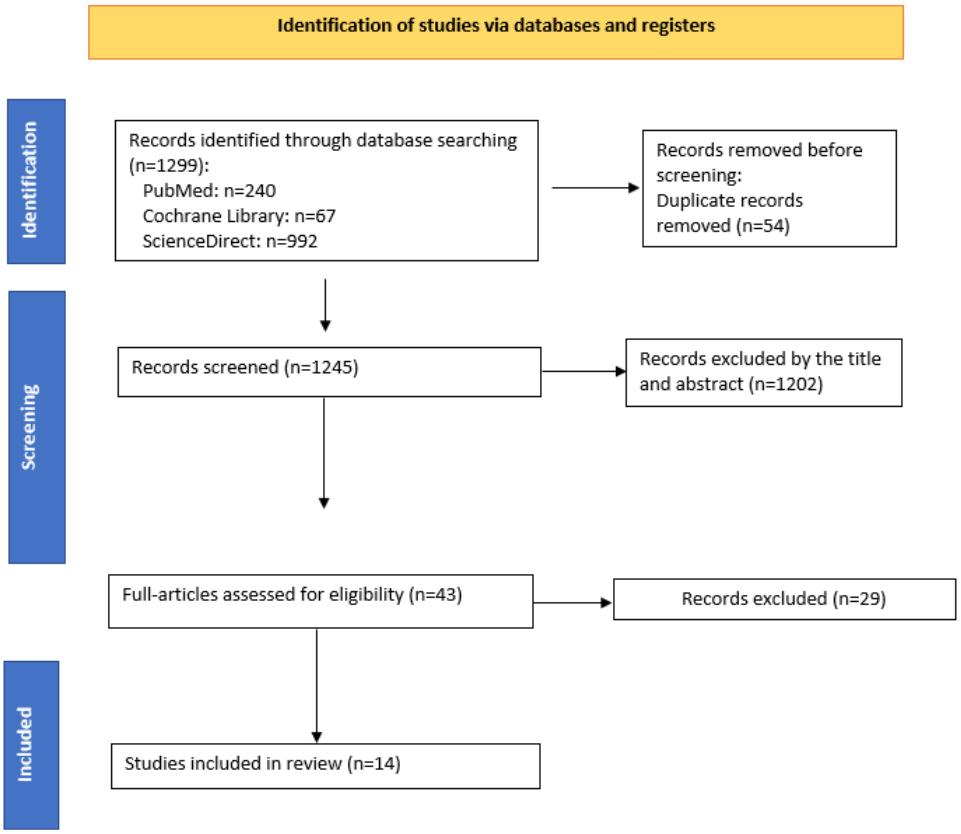

Fig-1: Flow chart according to the PRISMA statement

3.2 Study Characteristics:

14 relevant publications were identified as eligible according to the predefined inclusion criteria for this review: 4 articles were systematic reviews and 10 were cohort studies (4 retrospective and 6 prospective). Studies were collected with a publication date limited to 10 years, from 2014 to 2024.

3.3 Data Extraction and Synthesis

The 14 articles included in this systematic review and the data extracted from each study are shown in Table 3.

Table 3: Overview of included studies

Authors and Collaborators	Year	Study Design	Participants	Intervention	Primary Outcomes	Conclusion
Simon Mareike (3)	2014	Retrospective cohort study	30 patients (mean age 32.9); 60 teeth studied	Studied premolar derotation >10°, with and without attachments.	Precision of Premolar derotation =40%. Accuracy drops significantly for planned movement > 15° and >1,5° per aligner. No statistically significant difference was observed regarding the use of attachments.	Derotation is unpredictable and may require overcorrection or finishing sets.
Rossini Gabriele (4)	2015	Systematic review	11 studies (480 total patients), ages 13-72. [5]	Evaluated efficacy for intrusion, extrusion, rotation, tipping, and alignment. [6]	Rotation accuracy for canines was low (36%).	Aligners are ineffective for rotations of rounded teeth.
Grünheid Thorsten (5)	2017	Retrospective cohort study	30 non-extraction patients (mean age 21.6).	Comparison of achieved vs. Predicted positions using ClinCheck®.	Significant differences found for most teeth, but not clinically significant	High precision in non-extraction cases ; finishing sets may be needed to reach final goals.
Lombardo Luca (6)	2017	Retrospective cohort study	16 adults treated with F22 aligners.	Accuracy analysis of rotation, mesio-distal tipping, and V/L tipping.	Rotation of the maxillary premolars (54.0%) and mandibular canines (54.2%) were among the least accurate movements.	Efficacy is unequal across movement types; mandibular canine rotation is unpredictable.
Aikaterini Papadimitriou (7)	2018	Systematic review	22 studies, mostly non-extraction cases.	Global review of movement accuracy, overbite control, and distalization.	Insufficient control of canine/premolar rotations.	Invisalign® aligners allow predictable leveling and derotation of teeth, with the exception of canines and premolars, for which a slight degree of inaccuracy has been reported.

Authors and Collaborators	Year	Study Design	Participants	Intervention	Primary Outcomes	Conclusion
Nada Haouili (8)	2020	Prospective cohort study	38 patients (899 teeth) treated with Invisalign.	Comparison of 899 teeth with initial ClinCheck predictions.	Overall worst mean predictability observed with rotations (46%), especially mandibular 1st molars (28%).	System continues to improve but faces challenges with rotations.
Despina Koletsi (9)	2021	Systematic review and meta-analysis	7 studies focused on rotation.	Meta-analysis of rotation movement predictability	Canines showed lowest rotation accuracy (47.9% - 49.9%). Mandibular incisors and premolars were slightly higher.	Rotation predictability is generally low for anterior teeth and premolars; careful patient selection is advised.
G. Bilello (10)	2022	Prospective cohort study	10 patients (215 teeth).	Analysis of V/L tipping, tipping, rotation, and vertical movement.	Rotation accuracy was 86% overall.	High clinical success when planning is rigorous and auxiliaries/finishing sets are utilized.
Tommaso Castroflorio (11)	2022	Prospective cohort study	79 patients treated by expert operators.	Comparison of final tooth position vs. virtual plan.	Rotations of teeth with rounded crowns were among the least predictable movements with an approximate loss of 0.4° per planned degree; optimized attachments for maxillary canine and mandibular premolar rotation appear ineffective.	Biomechanical limits exist; attachment shapes and material properties require further optimization.
Aline Gonçalves (12)	2023	Systematic review	5 studies focused on maxillary incisors.	Evaluation of 8 movement types for upper incisors.	Rotation accuracy: -Central incisor: 48,7 % to 61,1 % -Lateral incisor: 41,8 % to 66,2 %	Maxillary incisor movement varies wildly by type; lateral incisors are generally more predictable than central incisors.
Vincenzo D'Antò (13)	2024	Prospective cohort study	45 participants (390 teeth) using Ordoline.	Analysis of rotation predictability using specialized attachments.	Global accuracy: 75-78%. Best: Mandibular lateral incisors (89.6%). Worst: 2nd molars (~60%).	Moderate accuracy for rotations; underperformance is common.
Luis Huanca Ghislanzoni (14)	2024	Prospective cohort study	21 subjects with mild malocclusions (Invisalign Lite).	28-week study comparing start, end, and software predictions.	Rotation is generally under-expressed. Attachments improve	Software over-predicts angular results; overcorrection planning and

Authors and Collaborators	Year	Study Design	Participants	Intervention	Primary Outcomes	Conclusion
					rotational movement, with a mean gain of approximately +1.4°.	auxiliaries are necessary.
Raquel Bueno MEDEIROS (15)	2024	Retrospective cohort study	56 patients (1,298 teeth).	Comparison of materials: EX30® vs. SmartTrack®.	No major difference for rotation between EX30 and SmartTrack.	Predictability decreases as movement magnitude increases; incisors move more accurately than canines or premolars.
Marco Migliorati (16)	2024	Prospective cohort study	17 patients treated with 3D printed aligners.	In-office printed aligners used for mild crowding.	Acceptable accuracy for rotation (72%).	3D printed aligners are a promising, effective alternative for mild crowding cases.

3.4 Risk of Bias in Included Studies:

➢ **Systematic reviews:**

Using AMSTAR 2 test, 2 studies presented a low risk of bias (Grade A), 2 studies were classified as moderately at risk of bias (Grade B) while 0 studies were assessed as low-quality reviews (Table 4).

Table 4: Risk of bias assessment according to AMSTAR 2

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Grade
Rossini *et al.,*	Y	Y	Y	Y	Y	Y	N	Y	Y	N	NM	NM	Y	PY	NM	N	B
Papadimitriou *et al.,*	Y	PY	Y	Y	Y	Y	N	Y	Y	N	NM	NM	Y	Y	NM	N	B
Koletsi *et al.,*	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	PY	Y	Y	N	Y	A
Gonçalves *et al.,*	Y	Y	Y	Y	Y	N	Y	Y	Y	N	NM	NM	Y	Y	NM	Y	A

Y: Yes; PY: Partially Yes; N: No; NM: No Meta-analysis.

➢ **Cohort studies:**

Using the NHLBI, NIH tool, 5 cohort studies were judged to be of high quality and 5 were rated as of moderate quality (Table 5).

Table 5: Risk of bias assessment according to NHLBI, NIH.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Qualité
Simon M.	Y	Y	U	Y	N	Y	Y	Y	Y	U	Y	Y	Y	Y	Moderate
Grünheid T.	Y	Y	U	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	High
Lombardo L.	Y	Y	U	Y	N	Y	Y	Y	Y	Y	U	Y	Y	Y	Moderate
Haouili N.	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	U	Y	Y	Y	High
Bilello G.	Y	Y	U	Y	N	Y	Y	Y	Y	Y	U	Y	Y	Y	Moderate
Castroflorio T.	Y	Y	U	Y	Y	Y	Y	Y	Y	Y	U	Y	Y	Y	High
D'Antò V.	Y	Y	U	Y	Y	Y	Y	U	Y	Y	U	U	Y	Y	Moderate
Ghislanzoni L.	Y	Y	U	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	High
MEDEIROS R.	Y	Y	U	Y	Y	Y	Y	U	Y	Y	Y	Y	Y	Y	High
Migliorati M.	Y	Y	U	Y	N	Y	Y	Y	Y	U	Y	Y	Y	Y	Moderate

Y: Yes; N: No; U: Uncertain.

3.5 Certainty Assessment:

The level of scientific evidence is assigned to each of the included studies according to the criteria outlined by the Oxford Center for Evidence-based Medicine [17] and presented in Table 7. All of the included articles were of grade B recommendation. Consequently, conclusions of a moderate level of evidence could be drawn from the review process.

Table 7: level of scientific evidence

Reference	Level of evidence	Grade of recommendation
[6]	2b	B
[7]	2a	B
[8]	2b	B
[9]	2b	B
[10]	2a	B
[11]	2b	B
[12]	2a	B
[13]	2b	B
[14]	2b	B
[15]	2a	B
[16]	2b	B
[17]	2b	B
[18]	2b	B
[19]	2b	B

4. DISCUSSION

4.1 Summary of Evidence:

It is well established that rotation is one of the least predictable movements with aligners. Derotation of cylindrically shaped teeth represents a major clinical challenge in particular, due to the rounded morphology, which promote loss of fit and slippage of thermoplastic aligners [18,19].

❖ **Premolars and canines:**

Simon *et al.,*[3] reported a mean accuracy of 37.5% (with attachments) and 42.4% (without attachments) for premolar derotation. In their systematic review, Rossini *et al.,* [4] cited prospective studies [20,21] that also demonstrated a low level of control over rotational movements. Nguyen and Chen [22], for example, reported an accuracy of 39% for canines and premolars. Using F22 aligners, Lombardo *et al.,*[6] confirmed these findings and observed that mandibular canine rotation was the least predictable movement (54.2%).

Haouili *et al.,*[8] likewise highlighted this low predictability, reporting an overall accuracy rate of 46%, with rotation being particularly difficult to achieve for canines, premolars, and molars. Although the SmartTrack protocol automatically plans optimized attachments for rotations exceeding 5°, rounded teeth still present difficulties in achieving adequate engagement with the aligners. This limitation had already been acknowledged by Grünheid *et al.,*[5] in a previous study published in 2017. Furthermore, the authors observed that the direction of rotation influenced accuracy in maxillary canines: distal rotations (37%) were markedly less accurate than mesial rotations (52%). As early as 2009, Kravitz *et al.,*[20] had shown that interproximal reduction improved the accuracy of canine rotation, suggesting that interproximal contact plays a key role in tracking failures. Haouili *et al.,* appear to support this hypothesis, proposing that the larger distal contact surface, together with the technical difficulty of performing interproximal reduction on the distal surface of the maxillary canine, could explain this reduced accuracy.

At the conclusion of their systematic review, Koletsi *et al.,*[9] corroborated previous findings and added that, despite advances in software, the predictability of rotational movements remains low, particularly for rotations exceeding 15°. The authors therefore recommend careful case selection and clear patient information regarding the limitations of aligner therapy. Castroflorio *et al.,*[11], on the other hand, reported that rotation of the first molars was the only movement exhibiting excellent accuracy, as previously noted in other studies [24,25]. Their data suggest a loss of approximately 0.4° for each planned degree at the level of maxillary canines and 0.3° per planned degree at the level of mandibular canines. Given that 70% of mandibular canines were equipped with optimized attachments, this more moderate loss compared with earlier data suggests that this type of attachment should be used systematically to improve clinical outcomes.

❖ **Incisors:**

With regard to incisor rotation, mean predictability values appear to be more favorable. Indeed, Haouili *et al.,* had already observed notable improvements for maxillary incisors and canines compared with the study by Kravitz *et al.,* [20]. Gonçalves *et al.,*[12] reported accuracy values ranging from 48.7% to 61.1% for central incisors and from 41.8% to 66.2% for lateral incisors, confirming the findings of Nguyen and Chen as well as Lombardo et al., who had already reported mean accuracy values of approximately 60% for incisors. However, the reduced size of lateral incisors limits the distance between the points of force application, thereby decreasing the generated moments and making the effectiveness of the movement more variable. Djeu *et al.,*[23] thus concluded, in their study on the Invisalign system, that it was capable of effectively correcting anterior tooth rotations and leveling the incisal edges.

Some studies have reported more favorable results regarding rotational accuracy with aligners, contrasting with the findings of earlier investigations. D'Antò *et al.,*[13], Bilello *et al.,*[10], and Migliorati *et al.,*[16] reported higher accuracy values for rotations, albeit with important caveats. D'Antò *et al.,* observed good accuracy for incisors (up to 89.6%) but lower performance for canines, premolars, and second molars, noting that these high values were biased by overperformance. Similarly, Bilello *et al.,* reported a mean accuracy of 86%, but achieved this by increasing both the number of aligners and the overall treatment duration. Finally, Migliorati *et al.,* reported a rotational accuracy of 72% using printed aligners, in a study limited by a small sample size.

Factors Influencing Predictability

1) Attachments

Attachments are almost systematically used for the correction of rotations, particularly for rounded teeth, in order to provide a point of engagement for the aligner on the crown. Simon *et al.,*[3] found no statistically significant difference in premolar derotation between groups with attachments (mean accuracy 37.5%) and without attachments (42.4%). The lower effectiveness observed in the attachment group was mainly attributed to poor patient compliance. It appears that when aligner fit is insufficient and no attachment is present on the tooth, the transmission of rotational force is merely reduced. By contrast, in the presence of an attachment, counter-moments may occur, inducing tooth movement in the opposite direction. When cases of poor compliance were excluded, a mean accuracy of 47.3% could have been achieved. Castroflorio *et al.,*[11] reported similar results for the rotation of maxillary canines and mandibular premolars, for which optimized attachments appeared not to function properly, attributing this to inadequate attachment design. In the study by Bilello et al., the use of optimized attachments proved insufficient, and incomplete rotations were the main reason for refinement phases. Nevertheless, a more recent study published in 2024 by Ghislanzoni *et al.,*[14] reported that attachments do indeed improve rotational predictability, with a mean gain in correction of +1.4° compared with the absence of attachments.

2) Amount and velocity of movement

Simon *et al.,*[3] reported that the accuracy of rotational correction was significantly reduced for rotations exceeding 15° (decreasing from 43.3% to 23.6%) and for movements planned at more than 1.5° per aligner (decreasing from 41.8% to 23.2%). These findings are consistent with those reported by Kravitz et al., who observed a significant decrease of up to 52.5% in the accuracy of canine derotation for rotations greater than 15° (20). Medeiros *et al.,*[15] noted that, on average, each additional planned degree of movement resulted in a loss of 0.35° of accuracy for rotation, in agreement with previous studies.

3) Interproximal reduction

Rossini *et al.,*[4] cited a prospective study [21] that evaluated the mean accuracy of canine rotation at 36%. Canines that underwent interproximal reduction exhibited the highest mean accuracy (43%). These results were corroborated by Haouili *et al.,*[8], who attributed the low predictability of distal canine rotation, among other factors, to the larger distal contact surface and the difficulty of performing interproximal reduction in this area.

4) Materials

The study by Medeiros *et al.,*[15] found no significant difference between EX30 and SmartTrack materials with regard to rotational movements.

4.2 Limitations:

This review presents several limitations that should be acknowledged. One of the main limitations lies in the heterogeneity of the included studies, which differ in their protocols, thereby making direct comparisons difficult and limiting the feasibility of robust meta-analyses. The overall level of evidence remains moderate, as the majority of the included studies are retrospective or prospective cohort studies, with a non-negligible risk of methodological bias. Moreover, certain complex movements and factors influencing predictability remain insufficiently investigated, which restricts the scope and generalizability of the conclusions.

In addition, the article selection was limited to studies available online and accessible free of charge, as well as those published or translated into French or English. This approach may have led to the exclusion of relevant scientific studies published in other languages, potentially introducing a selection bias. However, in the field of medical sciences, research is generally more likely to be translated into English when it reports significant findings, which may partially mitigate this limitation. Furthermore, the review was restricted to studies published within the last ten years, which may also represent an additional source of selection bias.

CONCLUSION

In conclusion, rotation is one of the least predictable movements with aligners, particularly for teeth with rounded crowns such as canines and premolars, due to the limited mechanical engagement of the aligner on the tooth surface. Mean accuracy values often range between 37% and 60%, with the highest predictability observed for incisors and the poorest performance for canines and premolars. The use of attachments—particularly optimized attachments—appears to improve accuracy, although their effectiveness also depends on patient compliance and attachment design and remains overall insufficient for reliable rotational correction. Interproximal reduction also facilitates rotation by reducing interdental contacts. The magnitude of the programmed movement and the

rate of aligner change influence accuracy, with a marked decrease in performance for rotations greater than 15° or those planned at more than 1.5° per aligner. Although improvements have been achieved, especially for incisors, rotational movements remain a major clinical challenge, requiring careful treatment planning and rigorous follow-up.

Nevertheless, the current lack of randomized clinical trials does not allow definitive conclusions to be drawn regarding the true predictability of rotation movements and the factors influencing them. Additional clinical and experimental research therefore remains essential to strengthen these findings.

Declarations Section:
Ethics approval and consent to participate: Not applicable.
Consent for publication: Not applicable.
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Authors' contributions:
MAB: study conception and design and data collection
RG and YA: analysis and interpretation of results
DI and WA: draft manuscript preparation
ST and AA: revised the text
All authors reviewed the results and approved the final version of the manuscript

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