Received: 29 November 2022 | Revised: 2 July 2024 | Accepted: 7 August 2024

DOI: 10.1111/ocr.12846

RESEARCH ARTICLE

Orthodontics & Craniofacial Research WILEY

Accuracy of clear aligners in the orthodontic rotational movement using different attachment configurations

Gianluigi Fiorillo[1] | Alessandra Campobasso[2] | Silvia Croce[1] | Umar Hussain[3] | Giovanni Battista[2] | Eleonora Lo Muzio[4] | Gualtiero Mandelli[1] | Alessandro Ambrosi[1] | Giorgio Gastaldi[1]

[1]Dental School, San Raffaele Vita-Salute University of Milan, Milan, Italy

[2]Department of Clinical and Experimental Medicine, University of Foggia, Foggia, Italy

[3]Department of Orthodontics, Saidu College of Dentistry, Swat, Pakistan

[4]Department of Translational Medicine and for Romagna, University of Ferrara, Ferrara, Italy

Correspondence
Alessandra Campobasso, Department of Clinical and Experimental Medicine, University of Foggia, Clinica Odontoiatrica Via Rovelli 50, 71122, Foggia, Italy.
Email: alessandra.campobasso@unifg.it

Abstract

Objective: To evaluate the accuracy of dental rotational movements using clear aligners with different attachment configurations.

Materials and Methods: This retrospective study analysed 212 teeth from 89 patients undergoing Invisalign treatment. Digital models were analysed after the virtual treatment plan (ST1) and after the first treatment phase (ET1) to evaluate the effective clinical rotational movement. The rotational movements of incisors, canines, and bicuspids were measured using data from the Clincheck Movements Table. ST1 and ET1 were compared to determine the actual rotational movement achieved (ST1-ET1). The presence or absence of attachments (rectangular or optimized) on teeth was analysed. The accuracy of rotational movements among attachment types was compared using the Kruskal-Wallis test. Multiple linear regressions were conducted with accuracy as the dependent variable and tooth type, gender, and age as predictors.

Results: Optimized attachments had the highest median accuracy (70%), followed by rectangular (65%), and without attachment (63%), with no significant differences ($p = .5$). There were no significant differences across age groups, genders, or tooth types. Baseline accuracy was 68.62% (95% CI: 56.03–81.20, $p < .001$). Age was a significant predictor (estimate = −0.30, 95% CI: −0.58 – −0.03, $p = .032$), indicating decreased accuracy with increasing age. The model's R^2 was 0.046, with an adjusted R^2 of 0.003, indicating minimal variance explained.

Conclusion: The addition of attachment configurations to clear aligners improves rotational accuracy, but not significantly. Further advancements in these configurations are needed to enhance the performance of the aligners.

KEYWORDS
attachment, clear aligner, rotation

1 | INTRODUCTION

In recent years, an increasing number of patients have been seeking orthodontic treatment,[1,2] and clear aligner Therapy (CAT) has become a key part of routine clinical practice.[3,4]

CAT represents a viable alternative to traditional fixed therapy, such as vestibular or lingual braces, due to the use of comfortable, removable clear appliances with a low aesthetic impact.[5,6]

These characteristics have made CAT popular among orthodontic patients, particularly adults.[7,8]

Additionally, three-dimensional (3D) treatment planning software enables clinicians to virtually pre-visualize treatment outcomes, also representing a motivational tool for patients.[7]

With the Clincheck® which is the dedicated software of Align technology, clinicians can simulate dental movements until achieving the final occlusion, allowing them to stage the sequence of tooth displacements and predict the therapy duration using Invisalign® aligners.[7]

Over the years, as reported in literature,[1,9] several improvements have been introduced in the Invisalign® system, including the change in the aligner material (form Exceed30® to SmartTrack®), advances in aligner design (SmartForce® Aligner Activation), and the update of Clincheck® software version (Invisalign®G8 with its SmartStage technology).

However, despite technological advances, several critical issues still remain regarding the actual reliability of CAT in expressing all predicted orthodontic movements, including rotation.[10–12]

In fact, each aligner is shaped with a predetermined mismatch between dental and aligner surfaces, which gradually moves the target teeth towards the correct position.[7,13–15]

Therefore, one factor that could influence the efficiency of CAT is the tooth shape because it could affect the fit between aligners and teeth.[16] Although anterior teeth can be successfully rotated using CAT,[1] the available literature has reported that the rotation of round-shaped teeth is the most unpredictable movement to correct with CAT.[10,17–19] The absence of interproximal undercuts in these tooth types could induce an incorrect force distribution, leading to a loss of fit of the aligner on the tooth surfaces.[16,20] Although Kravitz et al.[21] and Simon et al.[22] reported that the least predictable movement is premolar rotation, Lombardo et al.[17] suggested that the least accurate movement is the rotation of mandibular canines.

Considering the limitations of CAT for canine and premolar rotational movement, Papadimitriou et al.[1] suggested the use of additional attachments for these types of movements.

Composite attachments are bonded to the dental crowns to increase the aligner's retention and facilitate dental movements.[18]

Although several authors have demonstrated that the use of auxiliaries (such as attachments) significantly enhances the reliability and predictability of planned movements using aligners,[17,23,24] contrasting results were reported for rotational movements,[21,22,25] as confirmed by a recent review by Nucera et al.[25]

Therefore, the aim of the present study was to evaluate the accuracy of dental rotational movements with Invisalign® aligners using different attachment configurations, comparing the planned Clincheck simulation with the achieved clinical outcomes. The null hypothesis is that no differences exist between the expected and obtained rotation achievable by CAT.

2 | MATERIALS AND METHODS

2.1 | Study design, participants, and settings

A total sample of 998 adult patients who received Invisalign® (Align Technology, Santa Clara, CA, USA) aligner treatment was retrospectively enrolled. The sample was obtained from a single experienced orthodontist at the section of Orthodontics, Department of Dentistry, University of San Raffaele (Italy). All the procedures of this research adhered to the Declaration of Helsinki, and informed consent was obtained from all patients. The minimum sample size was 45 patients (15 in each group) calculated through openepi software (https://www.openepi.com/SampleSize/SSMean.htm) at 80% power, 95% confidence level using mean accuracy (%) of 72.8 ± 23.6 with optimized attachment and 48.1 ± 23.4 with conventional rotation attachment from previous similar study.[18] However, for normality assumption, we have taken all available 89 cases.

All patients met the following inclusion criteria: (1) treatment plan simulation using Clincheck® G8 software version; (2) age between 18 and 70 years old, without gender restrictions; (3) permanent dentition, without agenesis (except for third molars) or supernumerary teeth; (4) tooth rotation between 4° and 65° on the initial model; (5) 2° of planned rotation per stage; (6) a minimum of 14 aligners, without midcourse correction or additional aligners; (7) good compliance.

The main exclusion criteria were as follows: (1) treatment plan simulation using Clincheck G6 and G7 software versions; (2) severe maxillary contraction, extractive or surgical cases; (3) anomalies of dental crowns; (4) unerupted teeth; (5) ankylosis and primary eruption defect; (6) periodontal diseases; (7) missing teeth or implants or prosthetics; (8) more than 2° of planned rotation per stage; (9) auxiliaries for rotation correction (such as buttons, elastic chain, etc.).

According to the eligibility criteria, the final sample consisted of 89 adult patients, including 35 males and 54 females (mean age 30.90 ± 12.59 years old).

For each patient, initial digital casts were acquired with a TRIOS 3 (3Shape, Copenhagen, Denmark) colour intraoral scanner, and these pre-treatment scans were sent to Align Technology for Clincheck® planning.

For each treated arch, two digital models were obtained from Clincheck®: (1) virtual models of Clincheck planning, with the rotation simulated by the software; (2) virtual clinical models after the first phase of aligners or before the refinement phase.

2.2 | Digital measurements

For each maxillary and mandibular model, the amount of rotation was examined for different teeth, including central and lateral incisors, canines, first and second bicuspids.

These angular measurements were obtained from the Clincheck Tooth Movement Table, which is a software application developed by Align Technology to perform an automatic analysis report, which showed quantitative measurements for the simulated and effective rotations, avoiding any inaccuracy due to the manual detection of landmarks.

Using an automatic algorithm, the ClinCheck software calculates the degree of rotation of clinical crowns by comparing the initial position of each tooth with its simulated final position after the first aligner stage.

After performing the virtual treatment simulation, ClinCheck uses common reference points on the teeth to superimpose the initial scan with the simulated model, ensuring that all scans are aligned within a consistent spatial reference coordinate system.

The algorithm then calculates the degree of rotation for each tooth, from the initial positions (from the pre-treatment scan) to the simulated final positions (planned by the virtual simulation).

After the first stage of aligners, the pre-refinement scan is also aligned with both the initial scan and the simulated final model. The differences between the effective clinical rotations and the simulated virtual movements are automatically analysed, determining any remaining degrees of rotation required for each tooth.

Finally, 212 dental elements were analysed in the present study (83 for the maxillary arch and 129 for the mandibular one).

Based on these angular measurements, the models with the simulated rotation and the pre-refinement models were compared in order to evaluate:

- ST1 (simulated T1): the amount of rotational movement planned by Clincheck® software to reach the ideal position. It was expressed in degree (°).
- ET1 (effective T1): the amount of rotational movement (°) that the tooth has yet to perform to reach the ideal position, after the first phase of aligners or before the refinement.
- ST1-ET1 (actual rotational movement), namely the difference between ST1 and ET1 which indicated the amount of rotational movement actually obtained in the first treatment phase or before refinement.

For each measurement, the absence or presence of attachments on teeth was then analysed, considering different combinations of attachments:

1. No attachments (50 teeth).
2. Optimized attachments, automatically positioned on the buccal crown surface of the rotated teeth (96 teeth).
3. Vertical rectangular attachments, manually positioned on the buccal crown surface of the rotated teeth (66 teeth).

The overall accuracy for individual teeth and attachments was calculated in percentages (%) as follows:

$$Accuracy = \frac{ST1 - ET1}{ST1} \bullet 100$$

An accuracy value of 0% indicates that no rotation has occurred after the first phase of aligners, while an accuracy value of 100% indicates no residual rotation.

2.3 | Statistical analysis

Data analysis was done in R software 4.3.3 (Vienna, Austria). Due to skewed data, non-parametric tests were run. Median and interquartile ranges were calculated for the accuracy of rotational movements. Comparison was done for the accuracy of rotational movements among various configurations of the attachments using the Kruskal–Wallis test. Analysis was stratified by gender, age group, and tooth types. Multiple linear regressions were run using the accuracy of rotational movements as the dependent variable, while tooth type, gender, and age were predictors. The level of significance was set at $p \leq .05$.

3 | RESULTS

The mean age of the participants was 30.90 ± 12.59 years. Among females ($n = 156$, 73.58%), the rotated teeth were more than males ($n = 56$, 26.42%). The most commonly rotated tooth was the lower canine ($n = 40$, 18.87%), followed by the lower incisor ($n = 37$, 17.45%). Rotations were more common in the lower arch ($n = 129$, 60.85%) (Table 1). The outcome data (accuracy of Invisalign) was skewed, as shown by the histogram (Figure 1) and Shapiro–Wilk test ($p < .01$), so non-parametric tests were applied.

The highest median accuracy of rotational movement was for optimized attachments (median [IQR] = 70 [49, 81]), followed by rectangular attachments (median [IQR] = 65 [41, 82]), and least for without attachment (median [IQR] = 63 [39, 81]); however, the difference was not statistically significant ($p = .5$) (Table 2).

TABLE 1 Distribution of rotated teeth among genders, tooth types, and arches.

Variable	Characteristic	Rotated teeth, n (%)
Gender	Female	156 (73.58)
	Male	56 (26.42)
Tooth type	Lower 1st premolar	26 (12.26)
	Lower 2nd premolar	26 (12.26)
	Lower canine	40 (18.87)
	Lower incisor	37 (17.45)
	Upper 1st premolar	10 (4.72)
	Upper canine	28 (13.21)
	Upper central incisor	15 (7.08)
	Upper lateral incisor	30 (14.15)
Arch	Lower	129 (60.85)
	Upper	83 (39.15)

Accuracy of orthodontic rotational movement using different attachment configuration was not significant in all age groups and both in males and females (Figure 2; Table 3). Similarly, no significant difference was found for accuracy of orthodontic rotational movement using different attachment configurations for all teeth (Table 4).

The intercept estimate indicates a baseline median accuracy of rotational movement of 68.62 (95% CI: 56.03–81.20, $p<.001$). Most predictors, including specific teeth and gender, did not show statistically significant associations with rotational movement accuracy, as indicated by their p-values greater than 0.05. Age was a significant predictor with an estimate of −0.30 (95% CI: −0.58 – −0.03, $p=.032$), suggesting a slight decrease in accuracy with increasing age. The overall model had an R^2 of 0.046 and an adjusted R^2 of 0.003, indicating that the predictors explained only a small fraction of the variance in rotational movement accuracy (Table 5).

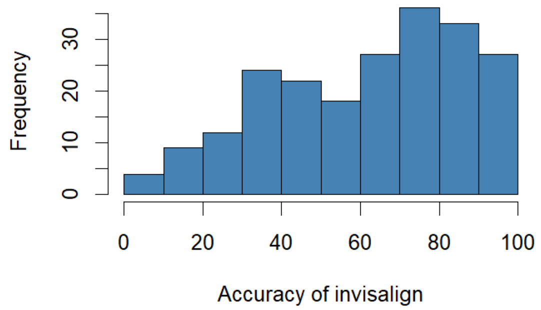

FIGURE 1 Distribution of outcome data.

4 | DISCUSSION

According to Andrews, rotation is the fourth key to normal occlusion, referring to the position of a tooth turned along its long axis in mesial or distal direction.[26] Although an ideal occlusion was achieved when no dental rotations were recorded within the arch,[27] the clinical expression of rotation movement using CAT is still a controversial topic, as reported in a recent review of Koletsi et al.[10]

Therefore, the objective of the present study was to determine the efficacy of Invisalign® for rotational movements after an initial series of aligners, using different types of attachments.

Clinically, this should be useful to minimize the need for additional aligners suggesting the use of different attachment geometries to improve the clinical achievement of the planned tooth movement.[27]

TABLE 2 Comparison of overall accuracy among attachments.

Characteristic	No attachment, $N=50$	Optimized, $N=96$	Rectangular, $N=66$	p-value[a]
Median (IQR)	63 (39, 81)	70 (49, 81)	65 (41, 82)	.5

[a]Kruskal–Wallis test.

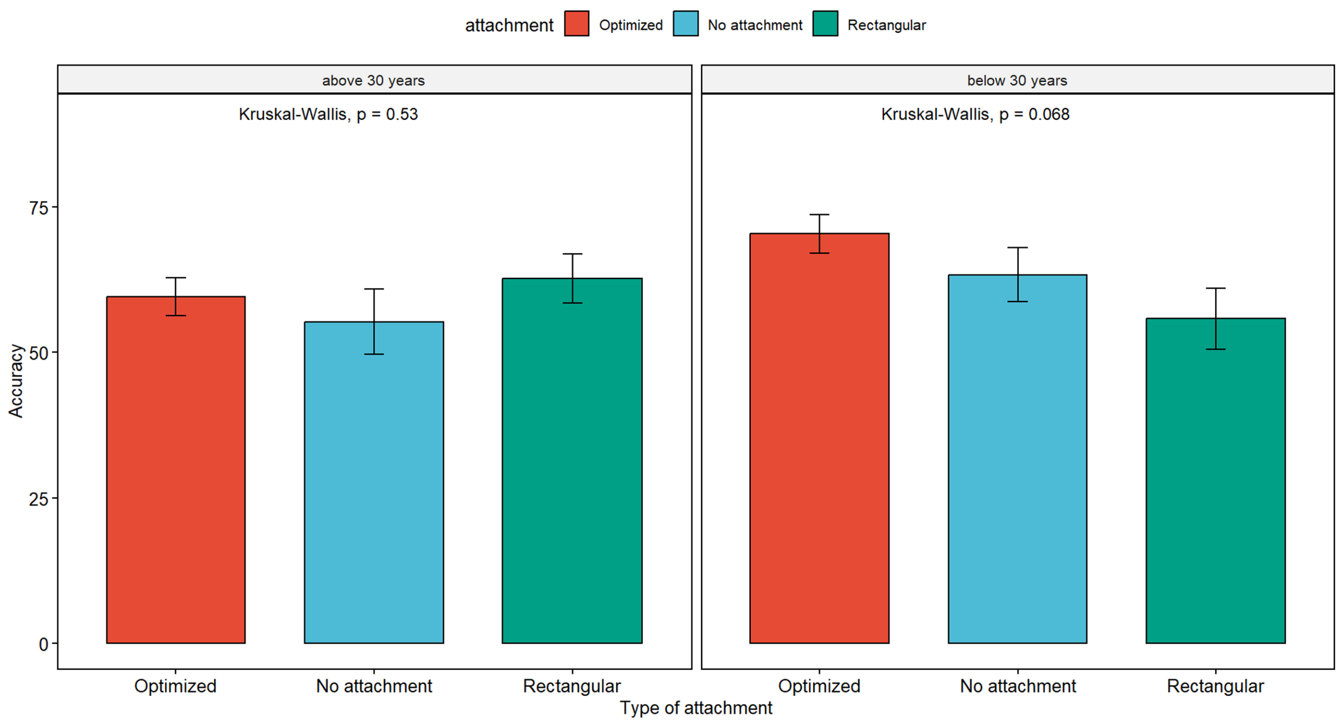

FIGURE 2 Accuracy of various attachments stratified by age groups.

TABLE 3 Comparison of accuracy among attachments in both genders.

Characteristic	No attachment	Optimized	Rectangular	*p*-value[a]
Male	73 (44, 87)	73 (49, 80)	70 (46, 86)	>.9
Female	58 (39, 78)	69 (48, 81)	63 (40, 76)	.3

[a]Kruskal–Wallis test.

TABLE 4 Comparison of accuracy among attachments for individual teeth.

		Type of attachment			
Characteristic	*n*	No attachment	Optimized	Rectangular	*p*-value[a]
Lower 1st premolar					
Median (IQR)	26	24 (24, 24)	77 (55, 82)	66 (40, 72)	.2
Lower 2nd premolar					
Median (IQR)	26	90 (73, 91)	68 (38, 85)	59 (38, 74)	.4
Lower canine					
Median (IQR)	40	63 (61, 65)	67 (48, 81)	80 (58, 91)	.4
Lower incisor					
Median (IQR)	37	55 (42, 85)	72 (54, 79)	37 (26, 54)	.5
Upper 1st premolar					
Median (IQR)	10	34 (34, 34)	83 (64, 91)	45 (45, 55)	.3
Upper canine					
Median (IQR)	28	48 (35, 62)	75 (57, 80)	49 (43, 73)	.2
Upper central incisor					
Median (IQR)	15	73 (53, 80)	59 (53, 60)	83 (83, 83)	.3
Upper lateral incisor					
Median (IQR)	30	52 (34, 72)	58 (40, 73)	69 (40, 85)	.6

[a]Kruskal–Wallis test.

TABLE 5 Regression analysis for accuracy with respect to tooth type, gender and age.

Predictors [Reference category]	Estimates	95% CI	*p*-value
(Intercept)	68.62	56.03 to 81.20	**<.001**
Teeth [lower 2nd premolar]	1.54	−12.05 to 15.14	.82
Teeth [lower canine]	7.2	−5.15 to 19.54	.25
Teeth [lower incisor]	−1.65	−14.18 to 10.89	.79
Teeth [upper 1st premolar]	−6.12	−24.33 to 12.09	.51
Teeth [upper canine]	1.57	−11.75 to 14.90	.82
Teeth [upper central incisor]	4.92	−10.96 to 20.80	.54
Teeth [upper lateral incisor]	1.04	−12.22 to 14.30	.88
Gender [male]	3.65	−4.12 to 11.42	.35
Age	−0.3	−0.58 to −0.03	.03
R^2/R^2-adjusted	0.046/0.003		

Rotation of teeth with rounded anatomies, such as bicuspids and molars, has been reported to be particularly challenging with plastic aligners without specialized attachments that enhance biomechanical capabilities.[28] The difficulties associated with rounded crown morphologies are due to three main factors.[29] First, in rounded crown configurations, the tangential forces produced during aligner-based tooth rotation, combined with a low coefficient of friction between the two surfaces, cause a slipping effect between the aligner and the tooth.[29] Second, the line of action of the normal force vectors resulting from tangential forces applied during the rotation of rounded crowns crosses at a short distance from the centre of resistance, resulting in weaker rotational moments.[29] Composite attachments with properly oriented active surfaces can overcome these issues by reconfiguring force vectors, increasing inter-vector distance, and blocking the slipping effect, leading to stronger and more effective rotational moments.[29] Additionally, unintended intrusion during rotational tooth movement has been observed.[30] In a study using finite element analysis,[31] researchers found that aligner-based rotation of an upper canine without attachments caused not only a lag of nearly 3 degrees compared to the corresponding aligner stage but also significant intrusive forces, 3.5 times greater than with attachments. Appropriate attachment design has been reported to mitigate this effect by orienting the active surface to reduce intrusive forces and promote extrusive tendencies.[31]

However, although some articles suggested that use of attachments could increase the effectiveness of rotational movement,[17] a recent review by Nucera et al.[25] reported conflicting results about the ability of attachments to improve dental rotation control.

In the present study, the highest overall accuracy was reported with optimized attachments (70%), followed by rectangular ones (65%), and when no attachments were used (63%). However, no significant differences were found among these percentages, suggesting the uncertain clinical efficacy of the attachments in the improvement of rotational movements.

When assessing canine rotational movement, Kravitz et al.[21] suggested that the use of attachments did not significantly improve the accuracy of canine rotation with the Invisalign system,[21] which is consistent with the current findings. However, in this previous study,[21] the most common attachment shape was vertical-ellipsoid, while in the present study optimized and rectangular attachments were analysed.

Similar results were also reported by Simon et al.[22] who found no significant differences of premolar rotation between groups with optimized or without attachments,[22] as well as Karras et al.[18] who reported that conventional attachments are as efficient as optimized attachments in the rotations of canines and premolars.

Partially in line with these results, another study of Simon et al.[32] reported enhanced results in premolar rotation using optimized attachments automatically placed by the software, compared to patients in which no attachment was used. Although in the present study no statistical significance was found, the use of optimized attachments was associated with the highest mean accuracy (70%).

According to the previous literature[21,22] and in line to the present outcomes, Momtaz[33] also reported no statistically significant differences in bicuspid rotation between groups with or without attachments, using in-office aligners. However, the author[33] found that the group with a rectangular attachment had the highest overall observable rotational correction. It is important to notice that this previous study considered in-office systems to produce aligners, which are not as sophisticated as those used by Align technology.[34,35]

A possible explanation for the present findings was reported by Papadopoulou et al.,[36] who demonstrated a substantial reduction to 50% of the applied force over time when Invisalign aligners were used with attachments.

Additionally, as shown by Koletsi et al.,[10] although various types of attachment have been suggested as potential prognostic factors for better efficacy of rotational tooth movement, this does not necessarily translate into an identified clinical effect.

This aspect should be explained considering that several factors seem to influence the rotation efficacy with CAT,[10] including the amount of total rotation movement,[22] the staging[16,22,37] and the interproximal reduction (IPR),[21] although Kravitz et al.[21] and Karras et al.[18] reported that IPR did not significantly affect the rotational accuracy.

Other factors that might affect the results reported in literature are the different superimposition methods among studies and also the inability to measure the patients' compliance.[27]

Further studies should be suggested to evaluate the influence of interproximal reduction on rotation movements and to compare different aligner materials.

Another important aspect shown in this study is the lack of significance in the accuracy among the various tooth types using different attachment configurations. Although it has been suggested that round-shaped crowns and tapered, longer crowns are associated with more or less difficulty in achieving rotational movement, respectively,[16] the present findings did not find any relationship between the tooth shape and the accuracy. This agrees with the contrasting findings reported in the literature, where there is no consensus on the type of tooth that shows the most favourable clinical response to rotational movement, considering that some studies have shown better results for premolars.[17] Even if in the meta-analysis of Koletsi et al.[10] the maxillary canines demonstrated the lowest percentage accuracy for rotational tooth movement (47.9%), while mandibular incisors presented the highest percentage accuracy for predicted rotational movement (70.7%), in their conclusions, the authors highlighted the high level of heterogeneity identified among the included studies.[10]

In the present study, the median accuracy of rotational movement was of 68.62%, which is higher compared to 41% reported by Kravitz et al.[37] using Invisalign® EX30 aligners, of 61.5% by Lombardo et al.[17] using F22 aligners, and of 50% reported by Haouili.[38]

Additionally, in the present study, the accuracy of rotational movement using different attachment configurations was not significant between males and females and in all age groups. However, a slight decrease in accuracy was reported with increasing age, and this may be due to the different mechanisms of bone remodelling in orthodontic tooth movement in the adults.[39]

5 | LIMITATIONS

Limitations of this retrospective study include the inability to account for certain variables, such as patient compliance, initial tip of the rotated teeth, presence or absence of space mesial and distal to rotated teeth, and the dimension of the clinical crowns, which could have affected the present results.

6 | CONCLUSIONS

The aim of this study was to investigate accuracy in rotational movements with CAT. Taken together, the measurements obtained from the retrospective observational study suggest that:

- There is no difference between optimized and rectangular attachments for improving the accuracy of rotational movement.
- Although the addition of attachments increases accuracy, this increase is not significant.
- The overall median accuracy for rotational movement was 68.62%.
- Tooth shape, gender, and age do not influence the accuracy of rotational movement.

Further advancements in the attachment configurations are needed to enhance the clinical accuracy of the aligner treatment in the rotational movement.

AUTHOR CONTRIBUTIONS

Fiorillo G., Campobasso A., and Croce S. have made substantial contributions to the conception, design of the work, and manuscript writing; Battista G., and Ambrosi A. have made substantial contributions to the acquisition and interpretation of data; Hussain U. have made substantial contributions to the analysis and interpretation of data, and to manuscript writing. Lo Muzio E., Mandelli G., and Gastaldi G. have drafted the work and substantively revised it. All authors agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

FUNDING INFORMATION

This research received no support from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST STATEMENT

Dr Gianluigi Fiorillo, one of the authors, often gives lecturers sponsored by 3M Unitek and Dentaurum. All other authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

ETHICS APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

ETHICAL INFORMATION

The study was conducted in accordance with the 1964 Helsinki declaration. Informed consent was obtained from all individual participants included in the study.

INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study.

ORCID

Alessandra Campobasso https://orcid.org/0000-0003-4726-8816
Giovanni Battista https://orcid.org/0000-0003-3543-686X

REFERENCES

1. Papadimitriou A, Mousoulea S, Gkantidis N, Kloukos D. Clinical effectiveness of Invisalign® orthodontic treatment: a systematic review. *Prog Orthod*. 2018;19(1):37.
2. Bruni A, Serra FG, Gallo V, Deregibus A, Castroflorio T. The 50 most-cited articles on clear aligner treatment: a bibliometric and visualized analysis. *Am J Orthod Dentofacial Orthop*. 2021;159(4):e343-e362.
3. Pango Madariaga AC, Bucci R, Rongo R, Simeon V, D'Antò V, Valletta R. Impact of fixed orthodontic appliance and clear aligners on the periodontal health: a prospective clinical study. *Dent J*. 2020;8(1):4.
4. Campobasso A, Lo Muzio E, Battista G, Ciavarella D, Crincoli V, Lo ML. Taxonomic analysis of Oral microbiome during orthodontic treatment. *Int J Dent*. 2021;2021:8275181.
5. Ke Y, Zhu Y, Zhu M. A comparison of treatment effectiveness between clear aligner and fixed appliance therapies. *BMC Oral Health*. 2019;19(1):24.
6. Dianiskova S, Rongo R, Buono R, Franchi L, Michelotti A, D'Antò V. Treatment of mild class II malocclusion in growing patients with clear aligners versus fixed multibracket therapy: a retrospective study. *Orthod Craniofac Res*. 2022;25(1):96-102.
7. Bilello G, Fazio M, Amato E, Crivello L, Galvano A, Currò G. Accuracy evaluation of orthodontic movements with aligners: a prospective observational study. *Prog Orthod*. 2022;23(1):12.
8. D'Antò V, Bucci R, De Simone V, Huanca Ghislanzoni L, Michelotti A, Rongo R. Evaluation of tooth movement accuracy with aligners: a prospective study. *Materials (Basel)*. 2022;15(7):2646.
9. Charalampakis O, Iliadi A, Ueno H, Oliver DR, Kim KB. Accuracy of clear aligners: a retrospective study of patients who needed refinement. *Am J Orthod Dentofacial Orthop*. 2018;154(1):47-54.
10. Koletsi D, Iliadi A, Eliades T. Predictability of rotational tooth movement with orthodontic aligners comparing software-based and achieved data: a systematic review and meta-analysis of observational studies. *J Orthod*. 2021;48(3):277-287.
11. Galan-Lopez L, Barcia-Gonzalez J, Plasencia E. A systematic review of the accuracy and efficiency of dental movements with Invisalign®. *Korean J Orthod*. 2019;49(3):140-149.
12. Robertson L, Kaur H, Fagundes NCF, Romanyk D, Major P, Flores MC. Effectiveness of clear aligner therapy for orthodontic treatment: a systematic review. *Orthod Craniofac Res*. 2020;23(2):133-142.
13. Barone S, Paoli A, Razionale AV, Savignano R. Computational design and engineering of polymeric orthodontic aligners. *Int J Numer Method Biomed Eng*. 2017;33(8):e2839.
14. Rongo R, Dianišková S, Spiezia A, Bucci R, Michelotti A, D'Antò V. Class II malocclusion in adult patients: what are the effects of the Intermaxillary elastics with clear aligners? A retrospective single center one-group longitudinal study. *J Clin Med*. 2022;11(24):7333.
15. Martina S, Rongo R, Bucci R, Razionale AV, Valletta R, D'Antò V. In vitro cytotoxicity of different thermoplastic materials for clear aligners. *Angle Orthod*. 2019;89(6):942-945.
16. Cortona A, Rossini G, Parrini S, Deregibus A, Castroflorio T. Clear aligner orthodontic therapy of rotated mandibular round-shaped teeth: a finite element study. *Angle Orthod*. 2020;90(2):247-254.
17. Lombardo L, Arreghini A, Ramina F, Huanca Ghislanzoni LT, Siciliani G. Predictability of orthodontic movement with orthodontic aligners: a retrospective study. *Prog Orthod*. 2017;18(1):35.
18. Karras T, Singh M, Karkazis E, Liu D, Nimeri G, Ahuja B. Efficacy of Invisalign attachments: a retrospective study. *Am J Orthod Dentofacial Orthop*. 2021;160(2):250-258.

19. Miller RJ, Kuo E, Choi W. Validation of align Technology's treat III digital model superimposition tool and its case application. *Orthod Craniofac Res*. 2003;6(Suppl 1):143-149.
20. Bucci R, Rongo R, Levatè C, et al. Thickness of orthodontic clear aligners after thermoforming and after 10 days of intraoral exposure: a prospective clinical study. *Prog Orthod*. 2019;20(1):36.
21. Kravitz ND, Kusnoto B, Agran B, Viana G. Influence of attachments and interproximal reduction on the accuracy of canine rotation with Invisalign. A prospective clinical study. *Angle Orthod*. 2008;78(4):682-687.
22. Simon M, Keilig L, Schwarze J, Jung BA, Bourauel C. Treatment outcome and efficacy of an aligner technique – regarding incisor torque, premolar derotation and molar distalization. *BMC Oral Health*. 2014;14:68.
23. Lione R, Paoloni V, Bartolommei L, et al. Maxillary arch development with Invisalign system. *Angle Orthod*. 2021;91(4):433-440.
24. Savignano R, Valentino R, Razionale AV, Michelotti A, Barone S, D'Antò V. Biomechanical effects of different auxiliary-aligner designs for the extrusion of an upper central incisor: a finite element analysis. *J Healthc Eng*. 2019;2019:9687127.
25. Nucera R, Dolci C, Bellocchio AM, et al. Effects of composite attachments on orthodontic clear aligners therapy: a systematic review. *Materials (Basel)*. 2022;15(2):533.
26. Andrews LF. The six keys to normal occlusion. *Am J Orthod*. 1972;62(3):296-309.
27. Maree A, Kerr B, Weir T, Freer E. Clinical expression of programmed rotation and uprighting of bilateral winged maxillary central incisors with the Invisalign appliance: a retrospective study. *Am J Orthod Dentofacial Orthop*. 2022;161(1):74-83.
28. Rossini G, Parrini S, Castroflorio T, Deregibus A, Debernardi CL. Efficacy of clear aligners in controlling orthodontic tooth movement: a systematic review. *Angle Orthod*. 2015;85(5):881-889.
29. Nanda R, Castroflorio T, Garino F, Ojima K. *Principles and Biomechanics of Aligner Treatment*. 1st ed. Elsevier; 2021:2021.
30. Elkholy F, Mikhaiel B, Schmidt F, Lapatki BG. Mechanical load exerted by PET-G aligners during mesial and distal derotation of a mandibular canine: an in vitro study. *J Orofac Orthop*. 2017;78(5):361-370.
31. Gomez J, Peña F, Valencia E, Mesa Benitez C. Effect of composite attachment on initial force system generated during canine rotation with plastic aligners: a threedimensional finite elements analysis. 2018.
32. Simon M, Keilig L, Schwarze J, Jung BA, Bourauel C. Forces and moments generated by removable thermoplastic aligners: incisor torque, premolar derotation, and molar distalization. *Am J Orthod Dentofacial Orthop*. 2014;145(6):728-736.
33. Momtaz P. The effect of attachment placement and location on rotational control of conical teeth using clear aligner therapy. 2016.
34. Venezia P, Ronsivalle V, Rustico L, Barbato E, Leonardi R, Lo GA. Accuracy of orthodontic models prototyped for clear aligners therapy: a 3D imaging analysis comparing different market segments 3D printing protocols. *J Dent*. 2022;124:104212.
35. Lo Giudice A, Ronsivalle V, Rustico L, Aboulazm K, Isola G, Palazzo G. Evaluation of the accuracy of orthodontic models prototyped with entry-level LCD-based 3D printers: a study using surface-based superimposition and deviation analysis. *Clin Oral Investig*. 2022;26(1):303-312.
36. Papadopoulou AK, Cantele A, Polychronis G, Zinelis S, Eliades T. Changes in roughness and mechanical properties of Invisalign(®) appliances after one- and two-weeks use. *Materials (Basel)*. 2019;12(15):2406.
37. Kravitz ND, Kusnoto B, BeGole E, Obrez A, Agran B. How well does Invisalign work? A prospective clinical study evaluating the efficacy of tooth movement with Invisalign. *Am J Orthod Dentofacial Orthop*. 2009;135(1):27-35.
38. Haouili N, Kravitz ND, Vaid NR, Ferguson DJ, Makki L. Has Invisalign improved? A prospective follow-up study on the efficacy of tooth movement with Invisalign. *Am J Orthod Dentofacial Orthop*. 2020;158(3):420-425.
39. Li X, Li M, Lu J, et al. Age-related effects on osteoclastic activities after orthodontic tooth movement. *Bone Joint Res*. 2016;5(10):492-499.

How to cite this article: Fiorillo G, Campobasso A, Croce S, et al. Accuracy of clear aligners in the orthodontic rotational movement using different attachment configurations. *Orthod Craniofac Res*. 2024;00:1-8. doi:10.1111/ocr.12846