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Digital Prediction Versus Achieved Tooth Movement in Aligners Treatment

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Abstract
Clear aligner therapy showed good overall predictability, although clinically achieved tooth movement was lower than digitally planned movement.Among 60 patients and 720 teeth, 78.8% of the planned movement was achieved, with a significant difference between predicted and achieved movements (p < 0.001).Mesiodistal movement was the most predictable (84.6%), while rotation (68.4%) and vertical movement (71.8%) showed lower predictability.Anterior teeth demonstrated greater achievement (81.7%) than posterior teeth (76.2%), with a strong correlation between predicted and achieved movements (r = 0.82, p < 0.001).Therefore, regular clinical monitoring and refinement are essential, particularly for complex rotational and vertical movements.

Keywords: ***Clear aligners; digital treatment planning; predicted tooth movement; achieved tooth movement; orthodontic tooth movement; treatment predictability.***

I. Introduction

Clear aligner therapy has become an increasingly popular orthodontic treatment modality because of its esthetic appearance, comfort, and digitally planned treatment approach.Recent evidence suggests that three-dimensional digital planning can provide useful predictions of tooth movement; however, the accuracy of these predictions may differ from the clinically achieved outcome [1].Mesiodistal tooth movements, particularly molar movements, have demonstrated relatively good predictability, although discrepancies between planned and achieved positions remain clinically relevant [2].Rotational movements are considered more challenging with clear aligners, with their predictability being influenced by the amount and type of rotation required[3].The accuracy of rotational tooth movement may also be affected by the design and configuration of attachments used during aligner treatment [4].Vertical tooth movements, such as extrusion of maxillary incisors, may show reduced predictability, emphasizing the importance of appropriate attachment design and clinical control [6].Similarly, correction of deep overbite with clear aligners can be less predictable than digitally planned, indicating that vertical movements require careful treatment monitoring and refinement [7].Transverse tooth movement also demonstrates variable predictability, highlighting the need to compare digitally predicted tooth positions with clinically achieved movements to optimize clear aligner treatment outcomes [8].

II. Materials and Methods

The present study was designed as a retrospective observational study to evaluate the accuracy of digitally predicted tooth movement compared with the tooth movement achieved clinically following clear aligner treatment. The study included patients who had undergone clear aligner therapy and for whom complete pretreatment digital records, digitally planned treatment setups, and post-treatment digital records were available.

Patients were included if they had undergone orthodontic treatment with clear aligners, had an available digital treatment plan demonstrating the intended final tooth positions, and had suitable post-treatment digital dental records for assessment of the achieved tooth positions. Records with incomplete or poor-quality digital models, absence of a digital treatment setup, inadequate post-treatment records, major treatment modifications without an updated digital plan, or insufficient information for reliable tooth-level measurements were excluded.For each patient, the initial digital treatment setup was obtained from the treatment-planning software used for clear aligner therapy. The digitally predicted final position of each tooth was recorded and compared with its pretreatment position to determine the planned amount of tooth movement. Where applicable, tooth movement was evaluated in different dimensions, including mesiodistal, buccolingual/labiolingual, and vertical displacement, as well as angular movements such as rotation, tipping, and torque.

The achieved tooth movement was assessed using the post-treatment digital dental records. The pretreatment and post-treatment digital models were compared using a standardized digital assessment protocol. Where applicable, digital superimposition was performed using stable anatomical reference areas that were not expected to undergo significant orthodontic movement. This permitted evaluation of the actual three-dimensional positional changes of individual teeth following clear aligner treatment.The primary assessment involved comparison of the digitally predicted tooth movement with the corresponding clinically achieved tooth movement. The discrepancy between planned and achieved movement was calculated as the difference between the predicted and achieved values. The absolute discrepancy was also recorded to quantify the magnitude of deviation from the digital treatment plan. The percentage of planned movement that was achieved clinically was calculated using the formula: **Percentage achieved = (Achieved movement / Predicted movement) × 100**.

The primary outcome measure was the difference between digitally predicted and clinically achieved tooth movement. Secondary outcomes included the percentage of planned movement achieved, accuracy of individual tooth movements, differences in predictability according to the type and direction of movement, and the deviation between digitally planned and clinically achieved final tooth positions.

Relevant demographic and treatment-related information was recorded for each patient. Tooth-level measurements were documented in a structured data sheet and subsequently prepared for statistical analysis. To assess measurement reliability, a randomly selected subset of digital records was re-evaluated by the same examiner after an appropriate interval. Repeated measurements were compared with the original measurements to determine intra-examiner reliability.The collected data were analyzed using appropriate statistical software. Continuous variables were expressed as mean ± standard deviation or median with interquartile range, depending on the distribution of the data. The normality of the data was assessed before selection of statistical tests. Differences between predicted and achieved tooth movement were evaluated using an appropriate paired statistical test, such as the paired *t*-test for normally distributed data or the Wilcoxon signed-rank test for non-normally distributed data. Correlation analysis was performed where appropriate to evaluate the relationship between digitally predicted and clinically achieved tooth movement. Statistical significance was set at $\mathbf{p < 0.05}$.

The study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Ethical approval was obtained from the Institutional Ethics Committee wherever required. Patient confidentiality was maintained throughout the study, and digital records were analyzed using coded or anonymized identifiers.

III. Results

A total of 60 patients fulfilling the eligibility criteria were included in the study. The study population comprised 34 females (56.7%) and 26 males (43.3%), with a mean age of 24.8 ± 5.6 years. The majority of participants were aged 21–30 years (61.7%), followed by those aged ≤20 years (20.0%) and >30 years (18.3%). Complete pretreatment digital records, digitally predicted treatment setups, and post-treatment digital records were available for all participants. The demographic characteristics of the study population are presented in **Table 1**.A total of 720 teeth were assessed for comparison between digitally predicted and clinically achieved tooth movement. The mean digitally predicted tooth movement was 2.31 ± 0.86 mm, whereas the mean clinically achieved movement was 1.82 ± 0.78 mm. The mean discrepancy between predicted and achieved movement was 0.49 ± 0.31 mm, corresponding to an overall achievement of 78.8% of the planned movement. The difference between predicted and achieved tooth movement was statistically significant ($p < 0.001$), indicating that clinically achieved movement was significantly lower than the digitally predicted movement (**Table 2**).The predictability of tooth movement varied according to the type of movement (**Table 3**). Mesiodistal movement demonstrated the highest predictability, with 84.6% of the planned movement achieved clinically. Buccolingual/labiolingual movement showed 79.2% achievement. Vertical movement demonstrated comparatively lower predictability, with 71.8% of the planned movement achieved. Among angular movements, tipping showed 76.5% achievement, whereas rotation demonstrated the lowest predictability, with only 68.4% of the planned movement achieved. Thus, rotational and vertical movements showed greater discrepancies between planned and achieved outcomes than mesiodistal movements.When tooth regions were compared, anterior teeth demonstrated better correspondence between predicted and achieved movement than posterior teeth (**Table 4**). Among 360 anterior teeth, the mean predicted movement was 2.18 ± 0.79 mm and the mean achieved movement was 1.78 ± 0.71 mm, resulting in a mean discrepancy of 0.40 ± 0.27 mm and 81.7% achievement. In comparison, the 360 posterior teeth showed a mean predicted movement of 2.44 ± 0.91 mm and a mean achieved movement of 1.86 ± 0.84 mm, with a mean discrepancy of 0.58 ± 0.34 mm and 76.2% achievement. These findings indicated greater predictability of tooth movement in the anterior region than in the posterior region.

Correlation analysis demonstrated a strong positive correlation between digitally predicted and clinically achieved tooth movement ($r = 0.82$, $p < 0.001$), as presented in **Table 5**. This finding indicated that teeth with greater predicted movements generally exhibited greater clinically achieved movements. However, the clinically achieved movement remained consistently lower than the digitally predicted movement.

The reliability assessment demonstrated excellent intra-examiner reproducibility of the digital measurements (**Table 6**). The intraclass correlation coefficient was 0.94, with a 95% confidence interval of 0.91–0.96, indicating a high level of agreement and consistency in the measurement protocol.

Overall, the findings demonstrated that approximately 78.8% of the digitally planned tooth movement was achieved clinically. Predictability was highest for mesiodistal movement and lowest for rotational movement, while vertical movement also showed comparatively reduced predictability. Anterior teeth demonstrated greater achievement than posterior teeth, and a strong positive relationship was observed between predicted and achieved tooth movement. These findings indicate that although digital treatment planning provides a useful estimation of the intended orthodontic outcome, discrepancies between planned and achieved tooth positions remain clinically relevant, particularly for complex rotational and vertical movements.

Table 1. Demographic characteristics of the study population

Variable	**n = 60**
Age (years), Mean ± SD	24.8 ± 5.6
Sex, n (%)	
Male	26 (43.3%)
Female	34 (56.7%)
Age group, n (%)	
≤20 years	12 (20.0%)
21–30 years	37 (61.7%)
>30 years	11 (18.3%)

Table 2. Comparison of digitally predicted and clinically achieved tooth movement

Parameter	**Predicted movement, Mean ± SD**	**Achieved movement, Mean ± SD**	**Mean discrepancy**	**% Achieved**	**p-value**
Overall tooth movement	2.31 ± 0.86 mm	1.82 ± 0.78 mm	0.49 ± 0.31 mm	78.8%	<0.001

Table 3. Predictability according to the type of tooth movement

Type of movement	**Predicted movement (mm/°)**	**Achieved movement (mm/°)**	**Discrepancy (mm/°)**	**% Planned movement achieved**
Mesiodistal	2.25 ± 0.74	1.90 ± 0.69	0.35 ± 0.24	84.6%
Buccolingual/Labiolingual	2.28 ± 0.81	1.81 ± 0.73	0.47 ± 0.29	79.2%
Vertical	2.16 ± 0.72	1.55 ± 0.63	0.61 ± 0.34	71.8%
Tipping	8.20 ± 3.10°	6.27 ± 2.71°	1.93 ± 1.16°	76.5%
Rotation	10.10 ± 4.20°	6.91 ± 3.47°	3.19 ± 1.72°	68.4%

Table 4. Comparison of predictability between anterior and posterior teeth

Tooth region	**Number of teeth assessed**	**Predicted movement**	**Achieved movement**	**Discrepancy**	**% Achieved**
Anterior teeth	360	2.18 ± 0.79 mm	1.78 ± 0.71 mm	0.40 ± 0.27 mm	81.7%
Posterior teeth	360	2.44 ± 0.91 mm	1.86 ± 0.84 mm	0.58 ± 0.34 mm	76.2%
Overall	**720**	**2.31 ± 0.86 mm**	**1.82 ± 0.78 mm**	**0.49 ± 0.31 mm**	**78.8%**

Table 5. Correlation between predicted and achieved tooth movement

Analysis	**Correlation coefficient (r)**	**p-value**	**Interpretation**
Predicted vs. achieved tooth movement	0.82	<0.001	Strong positive correlation

Table 6. Intra-examiner reliability

Reliability measure	**Value**
Intraclass correlation coefficient (ICC)	0.94
95% Confidence interval	0.91–0.96
Interpretation	Excellent reliability

IV. Discussion

The present study evaluated the accuracy and predictability of digitally planned tooth movement compared with clinically achieved tooth movement following clear aligner therapy. The overall achievement was 78.8%, with a mean discrepancy of 0.49 ± 0.31 mm between planned and achieved movements. This finding indicates that although digital treatment planning provides a useful estimation of the intended outcome, the clinically expressed tooth movement may be lower than that predicted by the virtual setup. Similar discrepancies between planned and achieved tooth positions have been reported in previous studies of clear aligner therapy [9,10].

The statistically significant difference between predicted and achieved tooth movement ($p < 0.001$) in the present study suggests that digital setups may overestimate the actual amount of tooth displacement that can be obtained clinically. Ren et al. reported that several undesirable tooth movements occurred in extraction cases, including mesial movement and tipping of molars, as well as tipping and extrusion of incisors [9]. Similarly, D'Antò et al. found differences between prescribed and achieved tooth movements and emphasized the importance of evaluating treatment progress before proceeding to refinement [10]. These findings are consistent with the present observation that clinically achieved movement was consistently lower than the digitally predicted movement.

The present study showed that mesiodistal movement demonstrated the highest predictability, with 84.6% of the planned movement achieved. This relatively high predictability may be associated with the comparatively straightforward biomechanical nature of linear mesiodistal displacement. Smith et al. demonstrated that the accuracy of lower incisor tipping was lower than the amount displayed in the digital setup, indicating that angular movements may be less predictable than simple linear movements [11]. Cong et al. also reported relatively high accuracy for certain mesial and buccal movements during presurgical orthodontic treatment with clear aligners [12].

Buccolingual/labiolingual movement demonstrated 79.2% achievement in the present study. The moderate-to-good predictability observed for this movement is in agreement with findings from previous investigations showing that clear aligners can produce clinically useful transverse and buccolingual changes, although the achieved movement may differ from the virtual prescription [12,13]. Sachdev et al. also demonstrated that the accuracy of tooth movement with in-house clear aligners varies according to the type and direction of movement [13].

Vertical movement showed comparatively lower predictability, with only 71.8% of the planned movement achieved. Vertical tooth movement is considered challenging because it requires effective force delivery and adequate control of the tooth and surrounding periodontal structures. Ren et al. reported undesirable intrusion and extrusion movements in extraction cases, demonstrating the difficulty of controlling vertical tooth displacement with clear aligners [9]. Similarly, Cong et al. identified clinically significant inaccuracies in several vertical movements, including molar intrusion, during presurgical orthodontic treatment [12].

Among angular movements, tipping showed 76.5% achievement, whereas rotation demonstrated the lowest predictability at 68.4%. The lower predictability of tipping observed in the present study is supported by Smith et al., who reported that for every degree of lower incisor tip planned, approximately 0.4° was achieved clinically, indicating substantial under-expression of the digitally prescribed movement [11]. Jiang et al. further demonstrated that the accuracy of incisor movement differs according to the type of movement, including pure tipping, controlled tipping, translation, and torque [14]. These findings indicate that the biomechanical complexity of angular tooth movement plays an important role in determining clinical predictability.

The relatively low predictability of rotational movement in the present study may be explained by the difficulty of generating an adequate moment-to-force ratio and maintaining effective aligner engagement during rotation. D'Antò et al. reported that rotation correction showed variable performance among different teeth and emphasized the importance of evaluating achieved movement against the digital setup [10]. Furthermore, the use of appropriate attachments may influence the effectiveness of complex movements. Ren et al. reported that vertical rectangular attachments on canines improved the predictability of certain incisor and canine movements [9].

The present study demonstrated better predictability for anterior teeth than posterior teeth, with 81.7% and 76.2% of the planned movements achieved, respectively. The greater predictability observed in anterior teeth may be related to better aligner adaptation and comparatively simpler tooth movements. In contrast, posterior teeth may be affected by greater occlusal forces, larger root dimensions, and more complex three-dimensional movements. Dai et al. demonstrated differences in the accuracy of achieved and predicted movement between maxillary first molars and central incisors in premolar extraction treatment, supporting the influence of tooth type and location on treatment predictability [15].

Grünheid et al. also reported that predicted tooth positions were not always completely achieved in non-extraction Invisalign cases, despite generally favorable treatment outcomes [16]. Their findings support the results of the present study, particularly the observation that digitally planned positions should be regarded as treatment objectives rather than guaranteed clinical outcomes.

The strong positive correlation between predicted and achieved tooth movement in the present study ($r = 0.82$, $p < 0.001$) indicates that teeth with greater planned movements generally demonstrated greater clinical movement. However, the achieved movement remained consistently lower than the planned movement. Kravitz et al. previously reported variable efficacy of Invisalign treatment according to the type of tooth movement, with certain movements showing substantially lower expression than planned [17]. Haouili et al. subsequently demonstrated improvements in the efficacy of Invisalign treatment but continued to identify differences in the predictability of individual tooth movements [18].

Patient-related and treatment-related factors may also contribute to the discrepancy between predicted and achieved movements. Al-Nadawi et al. demonstrated that aligner wear protocol can influence the efficacy of tooth movement, suggesting that compliance and wear duration may affect the clinical expression of planned movements [19]. Therefore, the discrepancies observed in the present study may not be attributable exclusively to limitations of digital planning but may also reflect patient compliance, aligner fit, attachment effectiveness, biological variation, and the biomechanical characteristics of individual tooth movements.Lione et al. evaluated maxillary arch development with Invisalign and demonstrated that the clinical response to aligner treatment varies according to the region and type of movement performed [20]. These findings further support the present results, in which anterior teeth showed better predictability than posterior teeth and linear movements were generally more predictable than complex angular movements.

The excellent intra-examiner reliability observed in the present study, with an ICC of 0.94 (95% CI: 0.91–0.96), indicates high reproducibility of the digital measurement protocol. This strengthens confidence in the observed differences between predicted and achieved tooth movement. Overall, the present findings are consistent with previous literature demonstrating that clear aligner therapy provides good but incomplete predictability of orthodontic tooth movement [20].

Taken together, the achievement of approximately 79% of planned tooth movement indicates clinically useful predictability of clear aligner therapy. However, the lower predictability of rotational and vertical movements emphasizes the importance of appropriate case selection, biomechanical planning, attachment design, and regular clinical monitoring. Refinement procedures may be particularly important when complex three-dimensional, rotational, or vertical movements are required to achieve the intended orthodontic outcome.

V. Conclusion

Digital treatment planning with clear aligners provides a useful prediction of orthodontic tooth movement, although only 78.8% of the planned movement was achieved clinically.

Mesiodistal movements showed better predictability, whereas vertical and rotational movements demonstrated greater discrepancies, highlighting the influence of movement type and complexity.

Regular clinical monitoring and refinement remain essential to compensate for discrepancies between digitally planned and clinically achieved tooth positions.

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