ORIGINAL ARTICLE
Volume 20 Issue 1 2025
10.21315/aos2025.2001.OA03
ARTICLE INFO
Submitted: 26/09/2024
Accepted: 23/03/2025
Online: 16/06/2025

Comparison of Horizontal and Vertical Tooth Movements in Erkodur vs Zendura FLX Clear Aligners

Nabilla Mohd Shukor[a], Al Imran Shahrul[b], Noraina Hafizan Norman[c*]

[a]*MSU Medical Centre, 1, Jalan Boling Padang 13/64, Seksyen 13, 40100 Shah Alam, Selangor, Malaysia*

[b]*Department of Family Oral Health, Faculty of Dentistry, Universiti Kebangsaan Malaysia, 50300 Kuala Lumpur, Malaysia*

[c]*Centre for Paediatric Dentistry and Orthodontic Studies, Faculty of Dentistry, Universiti Teknologi MARA, Sungai Buloh, 47000 Selangor, Malaysia*

*Corresponding author: noraina@uitm.edu.my

To cite this article: Shukor NM, Shahrul AI, Norman NH (2025). Comparison of horizontal and vertical tooth movements in Erkodur vs Zendura FLX clear aligners. *Arch Orofac Sci,* **20**(1): 29–41. https://doi.org/10.21315/aos2025.2001.OA03

To link to this article: https://doi.org/10.21315/aos2025.2001.OA03

ABSTRACT

The objective of this study was to assess and compare horizontal and vertical tooth movements between two clear aligner materials, Erkodur and Zendura FLX. Nineteen participants were divided into two groups, and received either Erkodur or Zendura FLX aligners, with digital models obtained at intervals over six months. Horizontal and vertical tooth movements were measured and compared using statistical tests, including the Mann-Whitney U test for overall movement and the Wilcoxon Signed-rank test for individual tooth movement between both groups. Overall, horizontal tooth movements between Erkodur and Zendura FLX were not statistically different, but vertical movements showed significant differences at the fifth and sixth months ($p < 0.05$). Significant differences between predicted and achieved horizontal tooth movement ($p < 0.05$) were observed for Erkodur on teeth 11, 41, and 35, and for Zendura FLX on teeth 17, 16, 25, 27, 45, 44, 41, 32, 36, and 37, predominantly indicating overcorrection, except for teeth 11 and 41 in the Erkodur group and tooth 41 in the Zendura group. Significant differences in vertical tooth movement ($p < 0.05$) were identified for Erkodur on teeth 14, 13, 11, 27, 44, 35, and 37, and for Zendura FLX on teeth 47, 45, and 44. Erkodur and Zendura FLX revealed no significant differences in initial horizontal tooth movements. However, significant disparities between the materials emerged in later stages of treatment, with both exhibiting notable discrepancies between predicted and achieved movement in both vertical and horizontal tooth movements over a six-month interval.

Keywords: *accuracy; clear aligner; Erkodur; Zendura*

INTRODUCTION

Clear aligners have gained popularity in recent years among patients seeking orthodontic treatment due to their improved aesthetics compared to traditional fixed appliances (Shi *et al.*, 2022). With advancements in CAD/CAM technology and intraoral scanning, the fabrication process for these appliances has become simpler (Narongdej *et al*., 2024). Clear aligners are manufactured by large companies such as Invisalign (Align Technology, USA) or in-house at smaller dental laboratories, similar to the fabrication of vacuum-formed retainers (Thakkar *et al*., 2023).

The biomechanics of clear aligners primarily rely on plastic material to deliver the necessary force for tooth movement. An ideal material should possess qualities such as springback, low stiffness, high stored energy, biocompatibility, and environmental stability. Despite the availability of numerous thermoplastic materials and ongoing research to improve the effectiveness of clear aligner therapy, the precision of tooth movements remains inadequate (Kravitz *et al*., 2009; Simon *et al*., 2014; Rossini *et al*., 2015; Lanteri *et al*., 2018; Haouili *et al*., 2020; Karras *et al*., 2021).

Manufacturers continue to strive to enhance the material properties of clear aligners to increase their effectiveness (Srinivasan *et al*., 2024). Polyester, co-polyester, polycarbonate, thermoplastic polyurethanes, and polypropylene are among the common materials used in clear aligners (Bichu *et al*., 2022). Numerous studies have evaluated the accuracy of Invisalign clear aligners, as it is one of the pioneers in clear aligner treatment and is widely used among consumers (Caruso *et al*., 2024). However, the materials used for Invisalign aligners are exclusive to the brand and not accessible to others. Therefore, dental labs or orthodontists wishing to manufacture their own clear aligners must use alternative materials such as Erkodur (Erkodent, Germany) or Zendura FLX (Bay Materials LLC, USA).

Zendura FLX features a unique tri-layer structure combining an elastomeric polyurethane inner core for flexibility and elasticity with a hard outer shell for increased elasticity. Erkodur, on the other hand, is primarily made from poly(ethylene terephthalate)-glycol (PET-G). Although studies have tested the mechanical strength of both Erkodur (Liu *et al*., 2016; Dalaie *et al*., 2021) and Zendura FLX (Koenig *et al*., 2022; Šimunović *et al*., 2023), to the best of authors' knowledge, there is limited evidence regarding their efficiency and accuracy in achieving orthodontic tooth movement as planned. The objective of our study was to evaluate and compare the accuracy of horizontal and vertical tooth movements using Erkodur and Zendura FLX clear aligner materials.

MATERIAL AND METHODS

Ethical Approval

Ethical approval for this study was granted by the institutional ethical review board [Ref. no: REC/10/2020 (FB/305)]. Written consent was obtained from all participants after providing detailed explanations regarding the study's purpose, potential risks, and benefits.

Trial Design

This study was a prospective, randomised, two-arm parallel controlled clinical trial with a 1:1 ratio aimed at evaluating the effectiveness of two thermoforming clear aligner materials. It was conducted at multiple centers across Selangor and Kuala Lumpur, including the Faculty of Dentistry, Universiti Teknologi MARA (UiTM) Sungai Buloh.

Study Participants

Convenient sampling was utilised to identify the study participants. The inclusion criteria encompassed individuals aged 18 to 45 years at the commencement of treatment, presenting with spacing or mild to moderate anterior crowding (less than 6 mm), deemed suitable for non-extraction orthodontic treatment with clear aligners, and considered fit and healthy. Exclusion criteria included patients requiring orthognathic surgery, those with systemic diseases, and individuals diagnosed with periodontal disease.

Sample Size Calculations

The sample size was calculated using G Power version 3.1.9.4, aiming to detect a significant difference of 0.5 mm in linear measurement (Grünheid *et al.*, 2017). A power of 95%, the number of measurements of 6 and an alpha level of 0.05 were set. It was determined that a minimum of eight participants was required. However, to accommodate a potential dropout rate of 20%, the sample size was increased to 10 participants per group.

Randomisation

Participants were randomly allocated to receive either Erkodur or Zendura FLX in a 1:1 allocation ratio using block randomisation of four numbers (Fig. 1). Concealed randomisation was ensured through the use of sequentially numbered opaque, sealed envelopes. These envelopes were assigned by the central trial coordinator (NHN).

Blinding

Blinding the operator was deemed infeasible due to the necessary communication between the operator and the aligner technician. However, efforts were made to blind the participants to the intervention, and the aligner group was also blinded during data analysis.

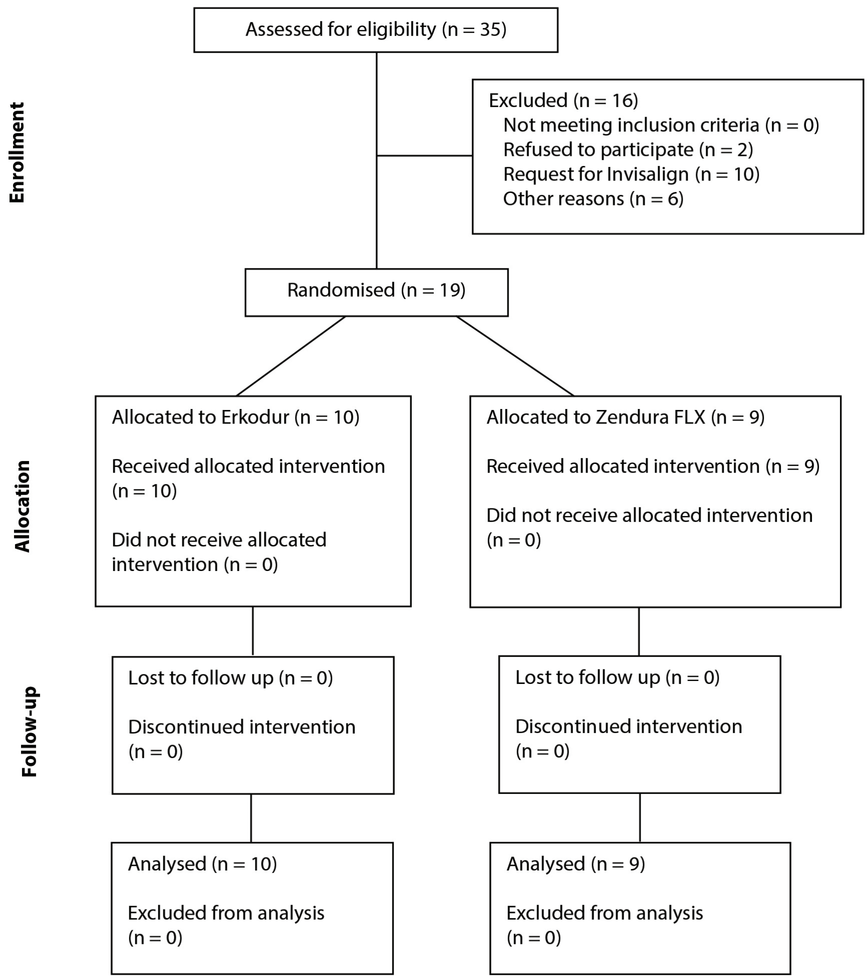

Fig. 1 Consolidated Standards of Reporting Trials (CONSORT) diagram (Schulz *et al.*, 2010).

Clear Aligner Procedure

After obtaining the patient's basic demographic information, the patient underwent a clinical assessment for crowding. The crowding was classified as mild (less or equal to 4 mm) or moderate (5 mm–8 mm). Subsequently, both the maxillary and mandibular arches were scanned using an i500 Medit intraoral scanner (Medit Corp., Korea) with consistent scanning specifications (Michelinakis *et al.*, 2020) i500; Medit, and Emerald; Planmeca. The digital files were saved in Standard Triangle Language (STL) format and shared with the dental technician laboratory using the Intrinsik DOTS application (intrinsic.ly, Hong Kong). A designated technician from the dental laboratory management oversaw the planning and production of both types of clear aligners. The treatment plan and aligner movements were designed using Blue Sky Plan software (Blue Sky Bio LLC, USA) and then reviewed by the operator. Both clear aligners were then manufactured according to the manufacturer's recommended guidelines on 3D-printed dental models. The thickness of Zendura FLX was 0.76 mm, while that of Erkodur was 0.8 mm.

Once fabricated, each aligner was stored in a clear pouch without any indication of its type. Patients were provided with two sequential sets of maxillary and mandibular aligners, representing each stage of treatment. Attachments were also placed as required by a single operator. The attachment was bonded using 3M Scotchbond etchant gel, 3M Single Bond Universal Adhesive bonding, and 3M Filtek Composite (3M, USA). Interproximal reduction (IPR) was also performed using Ortho Technology Galaxy interproximal diamond strips (Ortho Technology, USA), with no more than 0.25 mm per tooth side.

Each aligner was required to be worn for a minimum of 22 hours per day for two weeks before progressing to the next set (Al-Nadawi *et al.*, 2021). Text reminders were sent to each patient every two weeks to prompt them to switch to the next set of aligners (Timm *et al.*, 2022). In the event of any defects observed during aligner issuance, the aligner was discarded, and a new one was fabricated.

Patients underwent regular reviews every four weeks over a six-month period, during which both maxillary and mandibular arches were scanned using consistent parameters. Immediate review visits were scheduled within the same week if patients reported any breakages to address treatment issues promptly. Stopping rules were applied for both replacement and refinement of aligners.

Measurement Parameters

The initial models were labeled as "Initial", while subsequent stages were labeled as "Predicted" with corresponding stage numbers. The clear aligner stages progress over the course of six months. In month 1 (T1), it advances to Stage 2. By month 2 (T2), it transitions to Stage 4. At month 3 (T3), it reaches Stage 6. Progressing to month 4 (T4), it moves to Stage 8. By month 5 (T5), it enters Stage 10. Finally, in month 6 (T6), it is completed to Stage 12.

STL files generated at each follow-up visit were named as "Achieved" scans to reflect the actual results post-aligner wear. The initial, predicted, and achieved digital models were imported into the Medit Design application (app) (Medit Corp., Korea) and subsequently exported as STL files.

The predicted and achieved STL models were then superimposed onto the initial models (Fig. 2). Using the deviation display feature within the Medit Design app, the amount of deviation from the initial model was determined (Fig. 3). Deviation measurements were recorded by measuring the differences in horizontal and vertical positions of all teeth, excluding the third permanent molar. Measurements were recorded in millimeters with an accuracy of 0.000 mm. The specific measurement points are presented in Table 1. Tooth are recorded based on the FDI World Dental Federation notation (Santosh & Jones, 2024).

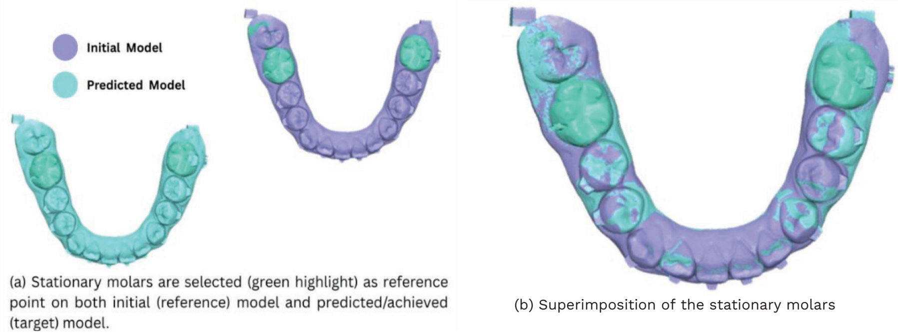

Fig. 2 (a) The predicted and achieved models were first uploaded according to arches and superimposition matching was performed with the desired arches accordingly. "Reference" object was uploaded with initial model (Stage 0), whereas the "Target" object was uploaded with either the predicted or achieved model. (b) The user-selected reference points mode was selected to allow regional superimpositions on untreated stationary molars.

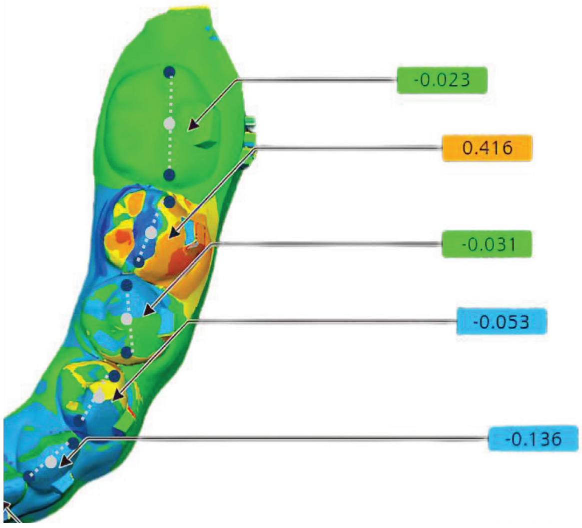

Fig. 3 Deviation display mode was selected to examine the deviation results between the target and reference data model. The differences in position and magnitude were recorded in millimetre for both horizontal and vertical position.

Table 1 The specific measurement points used in the study

Measurement	Points of measurement	Remarks
Horizontal displacement	Points were measured with the ruler tool at the middle of the incisal edges or cusp tips while viewing the models directly from the occlusal perspective.	Horizontal displacements refer to labial and lingual movement discrepancies. Directions were not considered.
Vertical displacement	Points were measured using the ruler tool at the middle of the incisal edges or cusp tips, viewed directly from a 90-degree angle in reference to the occlusal perspective.	Vertical movements were categorized into extrusion and intrusion based on predicted movement. A positive value would indicate extrusion, while a negative value indicates intrusion movement.

Error of Methods

Ten random stages were selected using the online randomisation tool, random.org (RANDOM.ORG, Ireland). The difference in horizontal and vertical movement was then remeasured after two weeks.

Statistical Analysis

Descriptive and analytical statistics were conducted using the Statistical Package for the Social Sciences (SPSS) software version 28.0 (IBM Corp., USA). To compare background demographic characteristics between the Erkodur and Zendura FLX groups, independent *t*-tests were employed for numerical data, while Fisher's exact test was used for categorical data.

A Mann-Whitney U test was utilised to compare the overall differences between groups for each stage of treatment, from stage T1 to stage T6. Additionally, a Wilcoxon signed-rank test was performed for each tooth to assess differences between predictive and achieved values, determining if there were any significant differences at the end of the six-month period. Statistical significance was set at $p < 0.05$ with a 95% confidence interval. The intra-operator reliability was evaluated by the intraclass correlation coefficient (ICC) (Koo & Li, 2016).

RESULTS

Baseline Characteristics

A total of 19 participants were enrolled in this study. The mean age was 29.73±7.7 years old. The majority of participants were female, accounting for 78.9% of the total. Most participants exhibited mild crowding in both the maxillary and mandibular arches. No significant differences were found between the two groups in terms of age, gender, or degree of crowding (Table 2).

Overall Movement

The differences between each clear aligner stage for the first six months of treatment in terms of horizontal and vertical movement are presented in Tables 3 and 4. The horizontal tooth movements for Erkodur and Zendura FLX up to stage T6 were not statistically significantly different. Vertical tooth movements between the aligners were not statistically different from stage T1 up to stage T4. However, as the aligners progressed to stages T5 and T6, there were statistically significant differences between Erkodur and Zendura FLX.

Horizontal Tooth Movement

Based on the results presented in Tables 5 and 6 for horizontal movement, there were significant differences between predicted and achieved tooth movement with $p < 0.05$ for Erkodur on teeth 11 ($p = 0.022$), 41 ($p = 0.011$), and 35 ($p = 0.008$). Similarly, for Zendura FLX, significant differences were observed on teeth 17 ($p = 0.007$), 16 ($p = 0.050$), 25 ($p = 0.007$), 27 ($p = 0.023$), 45 ($p = 0.007$), 44 ($p = 0.011$), 41 ($p = 0.035$), 32 ($p = 0.050$), 36 ($p = 0.041$), and 37 ($p = 0.021$). The majority of teeth exhibited significant differences, indicating overcorrection, except for teeth 11 and 41 in the Erkodur group, as well as tooth 41 in the Zendura group.

Vertical Tooth Movement

From the results of vertical movement (Tables 7 and 8), there were significant differences between predicted and achieved tooth movement with $p < 0.05$ for Erkodur on teeth 14 ($p = 0.022$), 13 ($p = 0.022$), 11 ($p = 0.022$), 27 ($p = 0.011$), 44 ($p = 0.008$), 35 ($p = 0.022$), and 37 ($p = 0.022$). Similarly, for Zendura FLX, significant differences were observed on teeth 47 ($p = 0.007$), 45 ($p = 0.009$), and 44 ($p = 0.011$).

Reliability

Table 9 shows excellent reliability, with an ICC of 0.93 for horizontal movements and 0.97 for vertical movements.

Table 2 Demographic characteristics of the participants

Characteristics	Total n (%)	Type of plastics		*p*-value
		Erkodur n (%)	Zendura FLX n (%)	
Age, mean (SD)	29.73 (8.44)	31.02 (8.01)	28.29 (9.15)	0.497[a]
Gender				
Male	4 (21.1)	2 (50.0)	2 (50.0)	> 0.95[b]
Female	15 (78.9)	8 (53.3)	7 (46.7)	
Malocclusion upper crowding				
Mild	14 (73.7)	8 (57.1)	6 (42.9)	
Moderate	3 (15.8)	0 (0.0)	3 (100.0)	0.065[b]
Spacing	2 (10.5)	2 (100.0)	0 (0.0)	
Malocclusion lower crowding				
Mild	13 (68.4)	7 (53.8)	6 (46.2)	
Moderate	5 (26.3)	2 (40.0)	3 (60.0)	> 0.95[b]
Spacing	1 (5.3)	1 (100.0)	0 (0.0)	

Notes: Values are presented as mean or number (%); [a]Independent *t*-test was performed; [b]Fisher's exact test was performed.

Table 3 Overall horizontal movement for Erkodur and Zendura FLX

Stage	Plastic type	Mean rank	Sum of ranks	*p*-value
T1	Erkodur	10.10	101.00	0.968
	Zendura FLX	9.89	89.00	
T2	Erkodur	9.10	91.00	0.497
	Zendura FLX	11.00	99.00	
T3	Erkodur	10.55	105.50	0.661
	Zendura FLX	9.39	84.50	
T4	Erkodur	10.33	93.00	0.277
	Zendura FLX	7.50	60.00	
T5	Erkodur	10.50	94.50	0.200
	Zendura FLX	7.31	58.50	
T6	Erkodur	11.17	100.50	0.059
	Zendura FLX	6.56	52.50	

Note: Mann-Whitney U test was performed.

Table 4 Overall vertical movement for Erkodur and Zendura FLX

Stage	Plastic type	Mean rank	Sum of ranks	*p*-value
T1	Erkodur	10.80	108.00	0.549
	Zendura FLX	9.11	82.00	
T2	Erkodur	9.30	93.00	0.604
	Zendura FLX	10.78	97.00	
T3	Erkodur	11.10	111.00	0.400
	Zendura FLX	8.78	79.00	

(*continued on next page*)

Table 4 (*continued*)

Stage	Plastic type	Mean rank	Sum of ranks	*p*-value
T4	Erkodur	9.89	89.00	0.481
	Zendura FLX	8.00	64.00	
T5	Erkodur	11.44	103.00	0.036*
	Zendura FLX	6.25	50.00	
T6	Erkodur	11.44	103.00	0.036*
	Zendura FLX	6.25	50.00	

Notes: Mann-Whitney U test was performed; *Statistically significant difference ($p < 0.05$).

Table 5 Horizontal movement of maxillary teeth for Erkodur and Zendura FLX at T6 (six months)

Tooth	Erkodur			Zendura FLX		
	Median predicted	Median difference (predicted - achieved)	*p*-value	Median predicted	Median difference (predicted - achieved)	*p*-value
17	0.003	−0.063	0.086	0.003	−0.127	0.007*
16	0.080	−0.093	0.759	0.002	−0.291	0.050*
15	0.305	0.025	0.444	0.112	−0.262	0.372
14	0.042	−0.143	0.575	0.374	0.132	0.212
13	0.178	0.036	0.333	0.001	−0.078	0.513
12	0.027	−0.036	0.878	0.826	−0.450	0.341
11	0.683	0.383	0.022*	0.000	0.111	0.592
21	0.053	−0.191	0.374	0.002	−0.021	0.065
22	0.006	−0.071	0.646	0.975	0.000	0.061
23	0.099	−0.097	0.507	0.018	−0.052	0.212
24	0.070	−0.235	0.674	0.091	−0.047	0.372
25	0.116	−0.197	0.959	0.003	−0.400	0.007*
26	0.015	−0.076	0.959	0.005	−0.093	0.258
27	0.008	−0.148	0.161	0.002	−0.192	0.023*

Notes: A negative value in the median difference column indicates that the achieved value was greater than the predicted one; Wilcoxon Signed-rank test was performed; *Statistically significant difference ($p < 0.05$).

Table 6 Horizontal movement of mandibular teeth for Erkodur and Zendura FLX at T6 (six months)

Tooth	Erkodur			Zendura FLX		
	Median predicted	Median difference (predicted-achieved)	*p*-value	Median predicted	Median difference (predicted-achieved)	*p*-value
47	0.003	−0.083	0.109	0.008	−0.222	0.109
46	0.080	−0.104	0.441	0.005	−0.147	0.084
45	0.305	−0.123	0.767	0.009	−0.436	0.007*

(*continued on next page*)

Table 6 (*continued*)

Tooth	Erkodur			Zendura FLX		
	Median predicted	Median difference (predicted-achieved)	*p*-value	Median predicted	Median difference (predicted-achieved)	*p*-value
44	0.042	–0.247	0.176	0.008	–0.329	0.011*
43	0.178	–0.092	0.406	0.038	–0.154	0.108
42	0.027	–0.006	0.123	0.028	–0.021	0.859
41	0.683	0.313	0.011*	0.660	0.588	0.035*
31	0.053	0.008	0.889	0.077	–0.061	0.889
32	0.006	–0.039	0.207	0.062	–0.032	0.050*
33	0.099	–0.123	0.859	0.003	–0.184	0.372
34	0.070	–0.021	0.866	0.003	–0.115	0.592
35	0.116	–0.065	0.008*	0.003	–0.2000	0.372
36	0.015	–0.110	0.859	0.016	–0.108	0.041*
37	0.008	–0.247	0.068	0.002	–0.208	0.021*

Notes: A negative value in the median difference column indicates that the achieved value was greater than the predicted one; Wilcoxon Signed-rank test was performed; *Statistically significant difference ($p < 0.05$).

Table 7 Vertical movement of maxillary teeth for Erkodur and Zendura FLX at T6 (6 months)

Tooth	Erkodur			Zendura FLX		
	Median predicted	Median difference (predicted - achieved)	*p*-value	Median predicted	Median difference (predicted - achieved)	*p*-value
17	–0.002	0.114	0.260	0.001	–0.095	0.674
16	0.004	–0.030	0.959	0.003	–0.179	0.086
15	0.010	–0.085	0.646	0.021	–0.353	0.441
14	0.002	–0.222	0.035*	0.140	–0.156	0.173
13	–0.046	–0.109	0.017*	0.002	–0.078	0.678
12	0.543	0.151	0.575	0.136	0.108	0.859
11	1.033	0.623	0.028*	0.940	0.770	0.374
21	1.345	0.424	0.169	0.343	0.203	0.876
22	0.554	0.352	0.146	0.464	0.193	0.594
23	0.138	0.133	0.114	0.018	–0.063	0.515
24	0.009	–0.038	0.574	0.070	–0.036	0.674
25	–0.002	0.052	0.575	0.003	–0.042	0.959
26	–0.006	0.109	0.202	0.005	–0.020	0.214
27	0.002	–0.127	0.017*	0.001	–0.182	0.779

Notes: A negative value in the median predicted column indicates an intrusion movement, and a positive value indicates an extrusive movement; A negative value in the median difference column indicates that the achieved value was greater than the predicted one; *Statistically significant difference ($p < 0.05$).

Table 8 Vertical movement of mandibular teeth for Erkodur and Zendura FLX at T6 (six months)

Tooth	Erkodur			Zendura FLX		
	Median predicted	Median difference (predicted - achieved)	*p*-value	Median predicted	Median difference (predicted - achieved)	*p*-value
47	0.003	–0.066	0.212	0.009	–0.197	0.008*
46	–0.009	0.174	0.286	0.002	–0.024	0.953
45	0.004	–0.163	0.546	0.021	–0.370	0.011*
44	0.140	–0.104	0.022*	0.008	–0.288	0.009*
43	0.226	0.087	0.058	0.026	–0.224	0.109
42	0.903	–0.174	0.643	0.104	–0.056	0.213
41	1.154	0.697	0.058	0.821	0.768	0.092
31	1.442	1.033	0.687	0.127	0.049	0.325
32	1.122	0.1865	0.209	0.329	0.235	0.213
33	0.005	0.550	0.295	0.003	–0.146	0.373
34	0.005	–0.075	0.308	0.010	–0.159	0.137
35	0.003	–0.122	0.044	0.002	–0.204	0.820
36	0.014	–0.215	0.242	0.002	–0.017	0.953
37	–0.005	0.163	0.017*	0.002	–0.069	0.313

Notes: A negative value in the median predicted column indicates an intrusion movement and positive value extrusive movement; A negative value in the median difference column indicates that the achieved value was greater than the predicted one; *Statistically significant difference ($p < 0.05$).

Table 9 Intra-examiner reliability assessment for accuracy of tooth movement

Single measure	ICC	95% Confidence interval	
		Lower bound	Upper bound
Horizontal movements	0.93	0.85	0.97
Vertical movements	0.97	0.94	0.99

DISCUSSION

The study results reveal a significant disparity between Erkodur and Zendura FLX in overall predicted and achievable vertical movement during stages 5 and 6. Initially, the vertical movement difference between the materials was insignificant until stage 5, indicating a cumulative difference in early treatment stages that became pronounced as treatment progressed. This underscores the importance of prolonged follow-up and monitoring, as teeth may deviate further from the intended path over time.

Regular follow-ups are essential, particularly due to the dependence on patient compliance. Our study protocol, which included two aligners per stage and frequent scans every four weeks, enabled early detection of deviations and timely provision of refinement aligners as needed. In contrast, direct-to-consumer aligner models, with limited face-to-face follow-ups (Wexler *et al.*, 2020), may lead to higher rates of lost movement tracking and inefficiencies in treatment (Belgal *et al.*, 2023) potentially prolonging treatment duration and increasing costs if unachievable movements are identified late in the process.

In the horizontal plane at the six-month mark, fewer statistically significant differences were observed between predicted and achieved movements compared to the vertical plane. Clinically insignificant discrepancies were noted for both materials, with minimal median differences (less than 0.5 mm) except for tooth 41 in the Zendura FLX group. Anterior teeth buccolingual movements were highly accurate, aligning with previous findings. Haouili *et al.* (2020) reported high accuracy (56%) for horizontal movements, contrasting with Kravitz *et al.*'s (2009) lower accuracy rates (37.6% to 53.1%).

The superior precision observed in buccolingual crown tip movements may be attributed to aligner material flexing predominantly in the buccolingual direction, coupled with the larger surface area available for pressure application on the buccolingual side of the teeth (Castroflorio *et al.*, 2024). However, challenges may arise in premolars and molars towards the terminal end of the arch, possibly due to inadequate aligner grip around the shorter clinical crowns of these posterior teeth. To enhance grip and accuracy, attachments can be applied to the posterior teeth, facilitating better retention and translation of programmed movements onto the tooth surface (Jedliński *et al.*, 2023).

The majority of teeth movements in the horizontal plane showed a negative value in the median difference column, indicating that the achieved value was greater than the predicted one. However, our study only recorded buccolingual measurements, neglecting mesiodistal tipping and torque expression, which could have affected the recorded displacement if more rotational movement was expressed. It is important to note that tooth movement is not independent from neighbouring teeth or anchoring teeth, and while distinct components of movement were examined, there is ultimately one resultant movement for each tooth (Upadhyay & Arqub, 2022). Despite this, the clinical significance of the small overexpression of horizontal movements was not clinically significant.

In the vertical plane, our data revealed the largest linear differences between predicted and achieved outcomes, with an extrusion of teeth 11 in the Erkodur group showing a difference of 0.623 mm (p = 0.028). The majority of inaccuracies were due to extrusion, accounting for 77.8% of teeth with significant differences between predicted and achieved movement. This aligns with Kravitz *et al.*'s (2009) findings, reporting extrusion as the least accurate tooth movement (29.6% accuracy). However, Charalampakis *et al.* (2018) found intrusion of incisors to be the most inaccurate, with the maxillary incisors showing a 1.5 mm difference. While our study reported fewer differences than Charalampakis *et al.* (2018) it is likely that with data collection extended to treatment completion, similar levels of inaccuracy would be observed.

For Erkodur, six significant differences in vertical movement were observed—two in intrusion and four in extrusion. No intrusion movements were planned for the Zendura FLX group; therefore, the three significant differences in vertical movement were related solely to extrusion. Hence, a comparison of intrusive movement between the two groups could not be made. However, Zendura FLX demonstrated greater overall accuracy in vertical movement despite its thinner construction. This improved performance may be due to Zendura FLX's tri-layer construction, in contrast to Erkodur's single-layer design.

Effective vertical movement requires not only elasticity but also sufficient impact strength to resist deformation caused by vertical occlusal forces. Zendura FLX's hard outer shell provides the necessary strength to withstand these forces, while its inner elastic core allows for controlled tooth movement.

LIMITATION

The superimposition process, conducted on posterior teeth (first permanent molar) due to their assumed stability (Harandi *et al.*, 2023), may have contributed to the magnitude of inaccuracy observed. This method was chosen due to the absence of stable anatomic structures in the Medit Design software. Furthermore, the planning was carried out by an experienced operator, which may limit the generalisability of this result.

CONCLUSION

This study comparing Erkodur and Zendura FLX clear aligners found no significant differences in initial horizontal tooth movements. However, notable differences emerged in the later stages of treatment. Additionally, both materials showed considerable discrepancies between predicted and achievable vertical and horizontal tooth movements by the six-month interval.

REFERENCES

Al-Nadawi M, Kravitz ND, Hansa I, Makki L, Ferguson DJ, Vaid NR (2021). Effect of clear aligner wear protocol on the efficacy of tooth movement. *Angle Orthod*, **91**(2): 157–163. https://doi.org/10.2319/071520-630.1

Belgal P, Mhay S, Patel V, Nalliah RP (2023). Adverse events related to direct-to-consumer sequential aligners—A study of the MAUDE database. *Dent J (Basel)*, **11**(7): 174. https://doi.org/10.3390/dj11070174

Bichu YM, Alwafi A, Liu X, Andrews J, Ludwig B, Bichu AY *et al.* (2022). Advances in orthodontic clear aligner materials. *Bioact Mater*, **22**: 384–403. https://doi.org/10.1016/j.bioactmat.2022.10.006

Caruso S, De Felice ME, Valenti C, Pagano S, Caruso S, Gatto R *et al.* (2024). An evaluation of the Invisalign® Aligner Technique and consideration of the force system: A systematic review. *Syst Rev*, **13**(1): 43. https://doi.org/10.1186/s13643-023-02437-5

Castroflorio T, Parrini S, Rossini G (2024). Aligner biomechanics: Where we are now and where we are heading for. *J World Fed Orthod*, **13**(2): 57–64. https://doi.org/10.1016/j.ejwf.2023.12.005

Charalampakis O, Iliadi A, Ueno H, Oliver DR, Kim KB (2018). Accuracy of clear aligners: A retrospective study of patients who needed refinement. *Am J Orthod Dentofacial Orthop*, **154**(1): 47–54. https://doi.org/10.1016/j.ajodo.2017.11.028

Dalaie K, Fatemi SM, Ghaffari S (2021). Dynamic mechanical and thermal properties of clear aligners after thermoforming and aging. *Prog Orthod*, **22**(1): 15. https://doi.org/10.1186/s40510-021-00362-8

Grünheid T, Loh C, Larson BE (2017). How accurate is Invisalign in non-extraction cases? Are predicted tooth positions achieved? *Angle Orthod*, **87**(6): 809–815. https://doi.org/10.2319/022717-147.1

Haouili N, Kravitz ND, Vaid NR, Ferguson DJ, Makki L (2020). Has Invisalign improved? A prospective follow-up study on the efficacy of tooth movement with Invisalign. *Am J Orthod Dentofacial Orthop*, **158**(3): 420–425. https://doi.org/10.1016/j.ajodo.2019.12.015

Harandi MT, Abu Arqub S, Warren E, Kuo CL, Da Cunha Godoy L, Mehta S *et al.* (2023). Assessment of clear aligner accuracy of 2 clear aligners systems. *Am J Orthod Dentofacial Orthop*, **164**(6): 793–804. https://doi.org/10.1016/j.ajodo.2023.05.028

Jedliński M, Mazur M, Greco M, Belfus J, Grocholewicz K, Janiszewska-Olszowska J (2023). Attachments for the orthodontic aligner treatment—State of the art—A comprehensive systematic review. *Int J Environ Res Public Health*, **20**(5): 4481. https://doi.org/10.3390/ijerph20054481

Karras T, Singh M, Karkazis E, Liu D, Nimeri G, Ahuja B (2021). Efficacy of invisalign attachments: A retrospective study. *Am J Orthod Dentofacial Orthop*, **160**(2): 250–258. https://doi.org/10.1016/j.ajodo.2020.04.028

Koenig N, Choi JY, McCray J, Hayes A, Schneider P, Kim KB (2022). Comparison of dimensional accuracy between direct-printed and thermoformed aligners. *Korean J Orthod*, **52**(4): 249–257. https://doi.org/10.4041/kjod21.269

Koo TK, Li MY (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med*, **15**(2): 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Kravitz ND, Kusnoto B, BeGole E, Obrez A, Agran B (2009). How well does Invisalign work? A prospective clinical study evaluating the efficacy of tooth movement with Invisalign. *Am J Orthod Dentofacial Orthop*, **135**(1): 27–35. https://doi.org/10.1016/j.ajodo.2007.05.018

Lanteri V, Farronato G, Lanteri C, Caravita R, Cossellu G (2018). The efficacy of orthodontic treatments for anterior crowding with Invisalign compared with fixed appliances using the Peer Assessment Rating Index. *Quintessence Int*, **49**(7): 581–587. https://doi.org/10.3290/j.qi.a40511

Liu CL, Sun WT, Liao W, Lu WX, Li QW, Jeong Y *et al.* (2016). Colour stabilities of three types of orthodontic clear aligners exposed to staining agents. *Int J Oral Sci*, **8**(4): 246–253. https://doi.org/10.1038/ijos.2016.25

Michelinakis G, Apostolakis D, Tsagarakis A, Kourakis G, Pavlakis E (2020). A comparison of the accuracy of 3 intraoral scanners: A single-blinded in vitro study. *J Prosthet Dent*, **124**(5) 581–588. https://doi.org/10.1016/j.prosdent.2019.10.023

Narongdej P, Hassanpour M, Alterman N, Rawlins-Buchanan F, Barjasteh E (2024). Advancements in clear aligner fabrication: A comprehensive review of direct-3D printing technologies. *Polymers*, **16**(3). https://doi.org/10.3390/polym16030371

Rossini G, Parrini S, Castroflorio T, Deregibus A, Debernardi CL (2015). Efficacy of clear aligners in controlling orthodontic tooth movement: A systematic review. *Angle Orthod*, **85**(5): 881–889. https://doi.org/10.2319/061614-436.1

Santosh ABR, Jones T (2024). Enhancing precision: Proposed revision of FDI's 2-digit dental numbering system. *Int Dent J*, **74**(2): 359–360. https://doi.org/10.1016/j.identj.2023.12.001

Schulz KF, Altman DG, Moher D (2010). CONSORT 2010 statement: Updated guidelines for reporting parallel group randomized trials. *BMJ,* **340**: c332. https://doi.org/10.1136/bmj.c332

Shi C, Feng Y, Hsiao YC, Smith J, Jin C, Farella M *et al.* (2022). Clear aligners brands and marketing claims: An overview of available information on the web. *Aust Orthod J*, **38**(2): 252–262. https://doi.org/10.2478/aoj-2022-0025

Simon M, Keilig L, Schwarze J, Jung BA, Bourauel C (2014). Treatment outcome and efficacy of an aligner technique - regarding incisor torque, premolar derotation and molar distalization. *BMC Oral Health*, **14**: 68. https://doi.org/10.1186/1472-6831-14-68

Šimunović L, Jurela A, Sudarević K, Bačić I, Meštrović S (2023). Differential stability of one-layer and three-layer orthodontic aligner blends under thermocycling: Implications for clinical durability. *Acta Stomatol Croat*, **57**(4): 286–299.

Srinivasan B, Padmanabhan S, Srinivasan S (2024). Comparative evaluation of physical and mechanical properties of clear aligners: A systematic review. *Evid Based Dent*, **25**(1): 53. https://doi.org/10.1038/s41432-023-00937-w

Thakkar D, Benattia A, Bichu YM, Zou B, Aristizabal JF, Fadia D *et al.* (2023). Seamless workflows for in-house aligner fabrication. *Semin Orthod*, **29**(1): 17–24. https://doi.org/10.1053/j.sodo.2023.01.004

Timm LH, Farrag G, Wolf D, Baxmann M, Schwendicke F (2022). Effect of electronic reminders on patients' compliance during clear aligner treatment: An interrupted time series study. *Sci Rep*, **12**: 16652. https://doi.org/10.1038/s41598-022-20820-5

Upadhyay M, Arqub SA (2022). Biomechanics of clear aligners: Hidden truths & first principles. *J World Fed Orthod* **11**(1): 12–21. https://doi.org/10.1016/j.ejwf.2021.11.002

Wexler A, Nagappan A, Beswerchij A, Choi R (2020). Direct-to-consumer orthodontics: Surveying the user experience. *J Am Dent Assoc*, **151**(8): 625–636. https://doi.org/10.1016/j.adaj.2020.02.025