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Original Article

Comparative Evaluation of Orthodontic Clear Aligner Attachments Using Scanning Electron Microscopy

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ABSTRACT

The success of clear aligner treatment depends largely on how effectively forces are transmitted through the aligner and attachment interface. This research investigated how well two clear aligner materials—Duran+ and Zendura FLX—fit against two attachment configurations—rectangular and optimized—at a microscopic level using scanning electron microscopy (SEM). Fifty-six samples were prepared and divided equally into four groups: Duran+ with rectangular attachments, Zendura FLX with rectangular attachments, Duran+ with optimized attachments, and Zendura FLX with optimized attachments (n = 14 per group). After bonding attachments to bovine incisors under standardized conditions, the aligners were thermoformed at 220 °C for 40 seconds. Cross-sectional analyses were carried out under SEM at 250× magnification, and gap widths were recorded at specific measurement sites (seven for rectangular and five for optimized attachments). Interfacial gaps ranged from 14.75 ± 1.41 µm to 91.07 ± 3.11 µm. Zendura FLX showed a tighter fit compared with Duran+ in rectangular attachments (42.10 ± 1.07 µm vs. 44.52 ± 1.51 µm, $p < 0.001$). Optimized attachments generally achieved better conformity than rectangular ones. Across all groups, gaps were widest along gingival margins (67.18–91.07 µm) and narrowest on flat buccal areas (14.75–20.98 µm). None of the evaluated combinations achieved a completely precise fit. Both aligner composition and attachment shape play important roles in microscopic adaptation, with multi-layer materials and optimized geometries providing superior contact. These outcomes help clarify mechanical factors that may contribute to the clinical shortcomings of clear aligner systems.

Keywords: Orthodontic attachments, Clear aligners, SEM, Material fit, Thermoforming

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Introduction

Growing patient interest in discreet orthodontic options has made clear aligners one of the most rapidly adopted treatment modalities in modern orthodontics [1, 2]. Since Kesling's early concept in the 1940s, these appliances have advanced far beyond their original purpose as simple retainers, evolving into precise systems capable of controlling complex tooth movements [3, 4]. This progress stems from developments in polymer technology, digital workflows, and the introduction of attachments—small composite features bonded to teeth that improve aligner grip and enhance force application [5, 6].

Compared with traditional fixed appliances, clear aligners offer several advantages, including superior aesthetics, comfort, and easier oral hygiene maintenance [7, 8]. The application of computer-aided design and manufacturing (CAD/CAM) has significantly refined their production, allowing greater customization and accuracy [9, 10]. In recent years, further technological leaps have expanded the potential of clear aligner systems. Artificial intelligence now contributes not only to digital fabrication but also to comprehensive treatment planning by assisting

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clinicians in facial analysis and the determination of ideal treatment outcomes [11]. Additionally, the rise of direct 3D printing has introduced a potential replacement for conventional thermoforming, reducing production limitations [12]. Together with multi-layer thermoplastic materials, these advances have strengthened both the mechanical integrity and precision of aligner systems [13]. The introduction of diverse attachment designs has also allowed for tooth movements previously considered unattainable with removable appliances [14]. Biomechanical research confirms that optimized attachments can deliver more efficient and controlled forces [15, 16], while layered materials improve the aligner's mechanical response [13].

Despite these advancements, the predictability of clear aligner therapy remains inconsistent. Clinical findings show that some tooth movements—such as extrusion, rotation, and root torque—are still difficult to achieve reliably [17–19]. Djeu *et al*. demonstrated that, while aligners can match fixed appliances for certain goals, they perform less effectively in managing buccolingual inclination, occlusal contacts, and inter-arch relationships [20]. Such limitations point toward mechanical and structural factors that continue to restrict clinical efficiency.

The precision of force delivery through the aligner–attachment interface is one of the main determinants of treatment success [15, 16]. Prior studies have shown that attachment design influences the resulting force systems and, consequently, movement predictability [21, 22]. Yet, the micro-level interaction between aligner material and attachment surface—where these forces are transmitted—has not been fully explored. Different analytical methods such as tensile tests, silicone impressions, and optical scans have been used to assess aligner fit, though each approach has notable drawbacks [6, 23, 24].

Recent imaging-based investigations have provided new insights into this microscopic interface. Research now focuses on improving contact accuracy between the aligner and attachment by modifying materials and manufacturing techniques [25]. Mantovani *et al*. were among the first to use scanning electron microscopy (SEM) to assess aligner fit, identifying measurable micro-gaps between aligners and tooth structures [26, 27]. Lombardo *et al*., using micro-computed tomography, reported significant variation in gap sizes across different aligner brands [28]. These findings suggest that microscopic adaptation may directly influence the clinical performance of aligner systems.

Several authors have also discussed the clinical relevance of interfacial gap size. Researchers [29] proposed that force transmission may be compromised when the gap exceeds 50 µm. Elkholy *et al*. [30] further observed up to a 40% reduction in force when the gap surpassed 100 µm, while Hahn *et al*. [31] reported clinically important discrepancies ranging between 50 and 200 µm. These consistent findings highlight the need to quantify aligner–attachment adaptation with high precision.

Therefore, the present study aimed to investigate the microscopic fit between two clear aligner materials (Duran+ and Zendura FLX) and two attachment types (rectangular and optimized) using SEM analysis. The null hypothesis assumed that aligner materials and attachment designs would exhibit complete and uniform adaptation at the interface, with no significant differences between groups.

Materials and Methods

Study design and sample size

This laboratory-based investigation compared how different aligner materials adapt to distinct attachment designs at a microscopic level. A sample size calculation was conducted in **G*Power 3.1**, using a reported effect size of 0.46 for interfacial gap variation between attachments and aligners. With a confidence level of 95% ($\alpha = 0.05$) and statistical power of 80%, the required number of samples was determined to be **56**, divided evenly into four experimental groups (n = 14 per group) [32].

Tooth selection and preparation

Fifty-six freshly extracted, caries-free bovine mandibular incisors were selected. Teeth were included only if they had intact enamel, no visible cracks or malformations, and consistent crown sizes. The use of bovine teeth followed previously validated methods in dental material research, as their enamel bonding characteristics are comparable to those of human teeth [33, 34].

After cleaning with pumice and water, the teeth were stored in distilled water at room temperature until processing. Each specimen was embedded vertically in cold-cured acrylic blocks to ensure stability during subsequent procedures. Digital surface scans of all mounted samples were then obtained using a **3Shape E1 scanner** (Copenhagen, Denmark), which provides dimensional accuracy in the range of 7–10 µm [35].

To avoid variability from multiple operators, all experimental steps—mounting, bonding, aligner formation, and sectioning—were performed by the same trained examiner (C.S.).

Attachment design and template fabrication

Two attachment geometries were digitally modeled using **Autodesk MeshMixer** (Version 3.5.474, San Rafael, CA, USA):

- **Rectangular attachment:** 3 mm width × 5 mm length × 2 mm height.
- **Optimized attachment:** 3 mm width × 5 mm length × 2.5 mm height with a curved profile.

These measurements were derived from standard clinical parameters and prior orthodontic research [6, 21]. The digital files were designed with a **0.1 mm offset** to account for resin thickness and ensure consistent adaptation [36]. A **2 mm overall template thickness** was selected based on previous mechanical evaluations, balancing flexibility and shape stability [37].

Templates were produced using a **Form 3 3D printer** (Formlabs, Somerville, MA, USA) with **IBT resin** printed at a 0.1 mm layer thickness. The resin's flexural modulus (2.2 GPa) provided adequate flexibility to adapt over convex tooth surfaces while maintaining the rigidity needed for accurate composite placement.

To improve fit accuracy, templates were designed with slightly extended edges and flexible margins that followed the natural curvature of bovine incisors. Before clinical simulation, each printed template was checked on its respective model to confirm proper seating and marginal adaptation without detectable gaps.

Post-processing procedures involved immersion in **99% isopropyl alcohol** for 20 minutes, followed by **UV curing** at 60 °C for 1 hour to ensure complete polymerization [38].

The complete digital-to-physical workflow—from CAD modeling to 3D-printed attachment template fabrication—is summarized in **Figure 1**, illustrating the standardized method used for consistent production across all specimens.

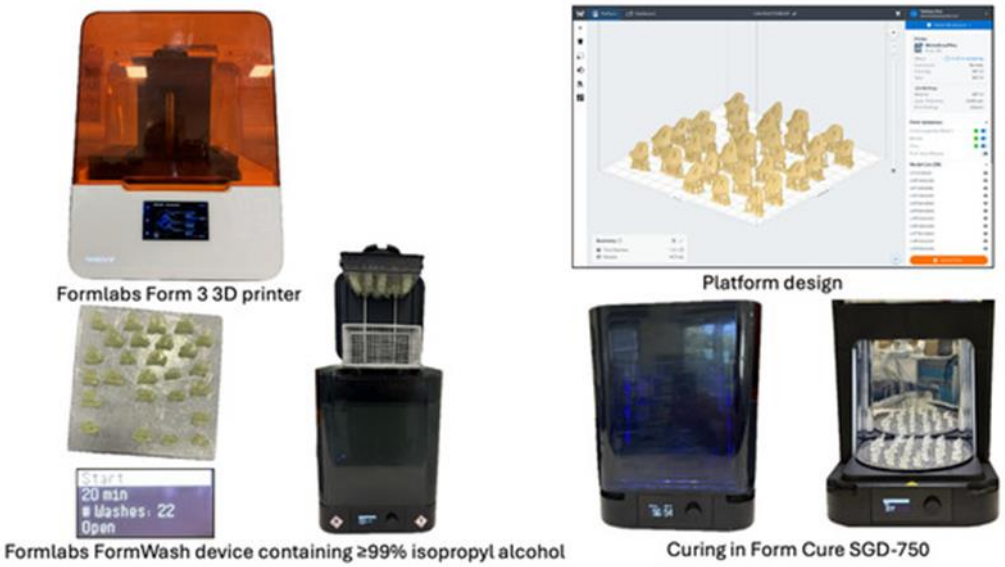

Figure 1. Workflow for attachment template fabrication.

Attachment bonding procedure

A standardized bonding method was applied to all specimens to ensure uniformity. The procedure involved the following steps:

1. The enamel surfaces were conditioned with 37% phosphoric acid for 30 seconds [39].
2. A thin layer of Transbond XT Primer (3M Unitek, Monrovia, CA, USA) was applied [40].
3. The bonding agent was light-cured for 20 seconds using a Woodpecker Dental iLed unit (Guilin, China).
4. Transbond XT composite resin (3M Unitek) was placed inside each attachment template.
5. Templates were seated on the tooth surface using a 50 g standardized force, verified with a Dentaurum force gauge.
6. Each composite-filled template was light-cured for 40 seconds [41].
7. After polymerization, templates were removed, and any excess composite was carefully trimmed with a scalpel under magnification to maintain the intended attachment contours and dimensions.

All attachments were bonded to the center of the buccal surface, positioned 4 mm from the incisal edge, guided by a digital placement reference. To standardize sectioning later in the experiment, a custom-made jig

was used to align each specimen at a consistent orientation through the midpoint of the attachment.

Fabrication of clear aligners

Two commercially available thermoplastic materials were evaluated:

- Duran+ (Scheu Dental, Iserlohn, Germany): 0.76 mm thick, single-layer PETG.
- Zendura FLX (Bay Materials, Fremont, CA, USA): 0.76 mm thick, triple-layer polyurethane featuring an elastic inner core and stiffer outer layers.

The materials were chosen based on their established clinical use and contrasting mechanical behavior [42, 43]. Duran+ exhibits a flexural modulus of approximately 2200 MPa, while the multi-layer Zendura FLX demonstrates a lower combined modulus (1100 MPa) but greater elasticity and shape recovery.

Each aligner was thermoformed individually over its corresponding tooth model to prevent inter-sample processing bias. The forming process was carried out on a Biostar thermoforming unit (Scheu Dental) at 220 °C for 40 seconds under a pressure of ≥4 bar, as recommended by the manufacturers [44]. No spacer foil was used so that material adaptation could be evaluated directly at the tooth–attachment interface. The formed aligners were trimmed 2 mm apical to the gingival margin according to standardized finishing protocols [45].

Scanning electron microscopy (SEM) evaluation

After aligner fabrication, the specimens were sectioned buccolingually through the center of each attachment using a precision cutting machine (Saeshin Strong 210, Daegu, Republic of Korea) fitted with a diamond-coated disc (Acurata GmbH, Thurmansbang, Germany). Continuous water cooling was applied throughout the process to avoid heat-induced distortion [46].

Before sectioning, samples were stabilized by embedding them in cold-cured epoxy resin, ensuring structural integrity at the aligner–tooth interface. Cutting was performed at a constant speed of 500 rpm with minimal applied pressure to reduce the risk of compressive artifacts.

After sectioning, specimens were inspected under a light microscope to confirm that no detachment or visible deformation occurred at the interface. Only samples meeting these criteria proceeded to SEM imaging.

Figure 2 presents an example of a sectioned tooth specimen prepared for SEM examination.



Figure 2. Cross-sectioned tooth sample.

The cross-sectioned specimens were sputter-coated with a thin layer of gold–palladium using a Leica EM ACE600 system (Wetzlar, Germany) to improve surface conductivity and enhance image resolution during SEM analysis [47, 48] **(Figure 3)**.



Figure 3. Coating tooth samples.

Specimens were analyzed using an EVO 40 Series Scanning Electron Microscope (Carl Zeiss AG, Jena, Germany) operated at 15 kV accelerating voltage, 10 mm working distance, and 250× magnification to capture detailed interfacial images [49].

Gap measurements were recorded at predefined anatomical points to ensure consistency across all samples:

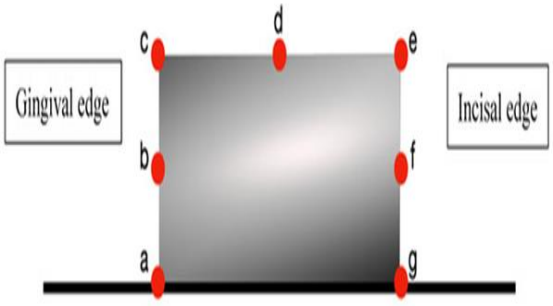

Figure 4. Seven points measured on the rectangular attachment.

- Rectangular attachments: Seven standardized locations were measured **(Figure 4)**, including:
- (a) gingival border — aligner–tooth interface at the gingival margin;
- (b) gingival midpoint — center of the gingival attachment surface;
- (c) gingival angle — transition zone between gingival and buccal surfaces;
- (d) buccal midpoint — center of the buccal surface of the attachment;
- (e) occlusal angle — junction between buccal and occlusal surfaces;
- (f) occlusal midpoint — center of the occlusal surface;
- (g) occlusal border — aligner–tooth junction at the occlusal margin.

Optimized attachments: Five specific measurement points were identified **(Figure 5)** to represent the critical regions of aligner–attachment adaptation.
Optimized attachments: 5 measurement points **(Figure 5)**;

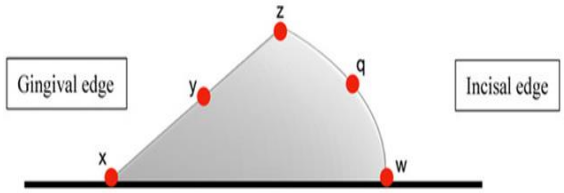

Figure 5. Five points measured on the optimized attachment.

For the optimized attachment design, five specific sites were selected to evaluate the fit between the aligner and the attachment **(Figure 5)**. These sites included the gingival margin, where the largest interfacial gaps are usually observed; the midpoint of the curved gingival surface, which reflects how well the aligner conforms to the beveled design; the buccal transition area, representing the slope between the attachment apex and the tooth surface; the occlusal midpoint along the gentle occlusal slope; and the occlusal margin, corresponding to the aligner–tooth junction at the crown's upper edge.
Fewer measurement points were required for the optimized attachments compared to the rectangular ones because the smooth, gradual contours of the optimized geometry eliminate sharp edges and abrupt transitions. The locations were chosen to capture typical variations in thermoformed aligner adaptation across the crown's gingival, middle, and occlusal regions. They also corresponded to areas likely to experience stress, the interfaces between attachment and enamel, and consistent landmarks to allow reliable comparison across specimens. In contrast, the rectangular attachments necessitated seven points to adequately assess all geometric discontinuities.
All measurements were conducted by a single trained examiner who was blinded to group assignments to minimize bias. Representative SEM images at 250× magnification, illustrating the measurement approach, are shown in **Figure 6**.

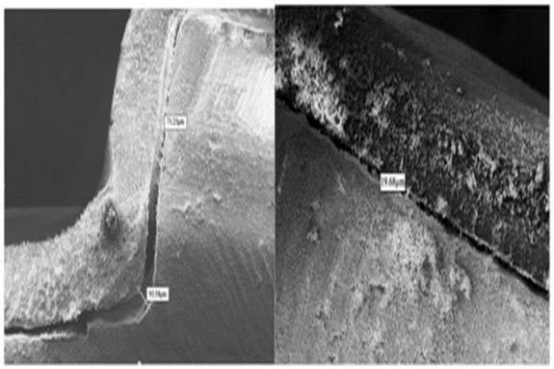

Figure 6. SEM images measurements (Mag = 250×).

After consulting with biostatistics experts, a single-examiner approach was adopted because the main outcome, interfacial gap measurement, was determined using **objective digital analysis** with **SmartSEM version 6.0** (Carl Zeiss AG) rather than subjective evaluation. The examiner's responsibilities were confined to identifying predefined anatomical landmarks and initiating software-assisted measurements. To ensure consistency and reliability, a set of strict standardization procedures was applied. These included the use of detailed photographic guides for each measurement location, reliance on automated SEM measurement functions to minimize manual errors, and confirmation of intra-examiner reliability, which showed excellent reproducibility with an **ICC greater than 0.95**. The examiner was also blinded to the experimental groups to prevent bias. All SEM images were assigned random codes by an independent researcher, and the coding key remained sealed until the completion of all measurements. Data collection was performed exclusively using these coded identifiers, with group allocation revealed only after all measurements and analyses were finalized.
For statistical processing, all data were analyzed using **SPSS version 24.0** (IBM Corp., Armonk, NY, USA). The **Shapiro–Wilk test** was employed to examine data distribution. Since the data did not follow a normal distribution, **Mann–Whitney U tests** were used for between-group comparisons. Results are presented as

mean ± standard deviation, with statistical significance defined at **$p < 0.05$**.

Results and Discussion

Measured gaps differed substantially depending on the location, attachment type, and aligner material. None of the material–attachment combinations achieved complete adaptation, as all samples exhibited measurable gaps at every evaluated site.

When comparing aligner materials for rectangular attachments, **Zendura FLX** demonstrated superior adaptation relative to **Duran+** at multiple points (Table 1). The mean interfacial gap for Zendura FLX was **42.10 ± 1.07 µm**, whereas Duran+ showed **44.52 ± 1.51 µm** (**$p < 0.001$**). Statistically significant differences were identified at the gingival border (**$p = 0.001$**), gingival midpoint (**$p = 0.022$**), gingival angle (**$p = 0.023$**), and occlusal border (**$p = 0.006$**), indicating that material selection plays a crucial role in adaptation, particularly in areas with complex geometries.

Table 1. Comparison of gap measurements (µm) between Duran+ and Zendura FLX aligners in rectangular attachment (mean ± SD).

Measurement Points	Duran+ (n = 14)	Zendura FLX (n = 14)	p-Value
a (Gingival border)	91.07 ± 3.11	85.77 ± 4.46	**0.001** **
b (Gingival midpoint)	70.71 ± 2.42	68.51 ± 2.34	**0.022** *
c (Gingival angle)	50.78 ± 2.26	48.75 ± 2.16	**0.023** *
d (Buccal midpoint)	20.98 ± 2.24	19.88 ± 1.74	0.159
e (Occlusal angle)	15.62 ± 1.58	14.75 ± 1.41	0.138
f (Occlusal midpoint)	18.87 ± 2.61	17.62 ± 2.49	0.206
g (Occlusal border)	43.70 ± 4.12	38.41 ± 3.40	**0.006** *

* $p < 0.05$, ** $p < 0.001$.

In the case of optimized attachments, the variation in adaptation between the two materials was minimal, with a statistically significant difference observed only at the buccal angle **(Table 2)**. Overall, the mean gap did not differ significantly between materials, measuring 37.30 ± 3.09 µm for Zendura FLX and 39.41 ± 3.20 µm for Duran+ ($p = 0.089$).

Table 2. Comparison of gap measurements (µm) between Duran+ and Zendura FLX aligners in optimized attachment (mean ± SD).

Measurement Points	Duran+ (n = 14)	Zendura FLX (n = 14)	p-Value
x (Gingival border)	69.91 ± 4.87	67.18 ± 4.92	0.152
y (Gingival midpoint)	29.62 ± 3.19	27.68 ± 3.27	0.127
z (Buccal angle)	32.38 ± 3.11	29.70 ± 3.07	**0.030** *
q (Occlusal midpoint)	18.25 ± 2.83	16.50 ± 2.96	0.122
w (Occlusal border)	47.28 ± 4.07	45.50 ± 3.93	0.248

Significant at $p < 0.05$

Comparison of attachment designs

Overall, optimized attachments exhibited superior adaptation compared with rectangular attachments, regardless of the aligner material used **(Table 3)**. For Duran+ aligners, the mean gap measured 39.41 ± 3.20 µm with optimized attachments, compared to 44.52 ± 1.51 µm with rectangular attachments. Similarly, for Zendura FLX aligners, optimized attachments showed an average gap of 37.30 ± 3.09 µm, whereas rectangular attachments had a mean gap of 42.10 ± 1.07 µm, highlighting the enhanced fit provided by the optimized geometry.

Table 3. Comparison of Average Space Distance (mean ± SD).

Attachment Type	Duran+	Zendura FLX	p-Value
Rectangular attachment	44.52 ± 1.51	42.10 ± 1.07	**0.000** **
Optimized attachment	39.41 ± 3.20	37.30 ± 3.09	0.089

Highly significant at $p < 0.001$

Regional variation patterns

Consistent gap distribution patterns were observed across all groups, regardless of material type. When rectangular attachments were analyzed without distinguishing between materials **(Table 4)**, clear regional differences emerged.

Table 4. Comparison of Average Space Distance (mean ± SD).

Measurement Points	Mean ± SD (μm)
a (Gingival border)	88.39 ± 4.62
b (Gingival midpoint)	69.61 ± 2.59
c (Gingival angle)	49.77 ± 2.40
d (Buccal midpoint)	20.43 ± 2.05
e (Occlusal angle)	15.19 ± 1.54
f (Occlusal midpoint)	18.24 ± 2.58
g (Occlusal border)	41.56 ± 4.30

The regional variation pattern was consistent:

- Largest gaps were consistently found at the gingival borders (range: 67.18–91.07 μm);
- Intermediate gaps occurred at the occlusal borders (range: 38.41–47.28 μm);
- Smallest gaps were observed at flat surfaces and acute angles (range: 14.75–20.98 μm).

This investigation demonstrates that current clear aligner systems and attachment designs do not achieve perfect fit at the microscopic level. Across all tested combinations, gaps ranging from **14.75 μm to 91.07 μm** were observed, highlighting potential limitations in force transfer and underscoring why certain tooth movements remain unpredictable in clinical practice.

Role of material characteristics

Zendura FLX exhibited superior conformity to attachments compared with Duran+, likely due to its multi-layer construction with an elastomeric core sandwiched between rigid outer layers. This design appears to allow better adaptation to complex geometries, particularly in areas with sharp transitions. Previous studies have suggested that multi-layer aligners provide higher retention and improved fit, with Cowley *et al*. reporting **8–12% better retention** compared to single-layer materials [45]. In our study, Zendura FLX improved average adaptation by approximately **5.5%** for rectangular attachments, indicating that material selection can meaningfully affect the efficiency of force delivery.

Interestingly, the difference between materials was more noticeable with rectangular attachments than optimized ones, suggesting a clear interaction between material flexibility and attachment shape. Rectangular attachments, with their sharp angles, pose greater challenges for alignment, while the smoother curves of optimized attachments allow even single-layer materials to adapt more effectively. These findings are consistent with Ryokawa *et al*., who demonstrated that material composition affects stress distribution, relaxation, and contact with dental surfaces [50].

Effects of attachment geometry

Optimized attachments showed roughly **11–12% better fit** than rectangular attachments, independent of the aligner material. Beyond their smoother contours, optimized designs incorporate features such as movement-specific orientations, variable thickness, and strategic undercuts to improve load distribution and functional retention. The improved adaptation observed in this study likely reflects both the smoother surface facilitating thermoforming and the biomechanical efficiency of the design. These results build on the work of Savignano *et al*., who emphasized that attachment geometry plays a critical role in shaping force vectors [21].

It is important to distinguish adaptation from retention. While Dasy *et al*. reported higher retention with rectangular attachments [6], our findings show better material-tooth contact for optimized attachments. Retention measures the force required to dislodge an aligner, whereas adaptation measures the intimate contact needed for effective force transmission. Both are clinically relevant: insufficient retention risks aligner displacement, while poor adaptation can lead to unpredictable tooth movement. Thus, optimized attachments may compensate for lower retention through more precise force application, explaining their clinical preference despite contrasting retention findings.

However, optimized attachments are not without limitations. Studies indicate that they do not consistently outperform conventional designs for all movements, often achieving only partial planned displacement and sometimes necessitating overcorrection [51]. Moreover, root control attachments in optimized designs may degrade faster due to surface wear, particularly after four months, reducing their effectiveness relative to rectangular attachments [52]. This wear can compromise treatment outcomes for movements such as canine distalization and may require attachment rebonding during therapy.

Current research indicates that the effectiveness of orthodontic attachments varies depending on the specific type of tooth movement, and no single design consistently outperforms all others. For example,

optimized attachments tend to perform best for lateral incisor rotation [53], whereas conventional vertical attachments are more effective for controlling mesio-distal angulation, and horizontal attachments are superior for managing vestibulo-lingual torque [53]. In extrusion movements of the maxillary lateral incisor ranging from 0.3 to 2.5 mm, horizontal attachments have been shown to be more efficient than optimized designs [54]. Additionally, rectangular attachments appear to maintain long-term efficiency in canine distalization, likely because they are less affected by surface wear over time [52]. These findings suggest that attachment selection should be tailored to the specific clinical objective, taking into account both immediate performance and durability, rather than applying a single attachment type universally.

Regional differences and clinical implications

This study also addressed the variability in aligner adaptation across different areas of the clinical crown. Standardized measurement points at gingival, middle, and occlusal regions were used to capture the full spectrum of fit. Consistent with previous findings by Krey *et al*. [43], gaps were not uniform, with the largest discrepancies occurring at the gingival margins (67.18–91.07 μm) and smaller gaps observed in the occlusal region (38.41–47.28 μm). This pattern reflects the uneven stretching and thinning of aligner material during thermoforming, particularly in areas with greater draw depth.

The observed regional variation provides a mechanical explanation for some movement-specific limitations reported in clinical practice. The relatively large gaps at gingival margins may contribute to the reduced predictability of extrusive movements, which rely heavily on force application in these areas [17]. In contrast, flatter buccal surfaces, where gaps were smaller, may facilitate more efficient movements that depend on direct aligner–tooth contact. It is important to note that not all movements require attachments; simple tipping often occurs effectively without them, as the aligner alone can apply sufficient force above the tooth's center of resistance [55]. However, for more complex movements such as bodily translation or root torque, where precise force coupling is crucial, attachment fit becomes critical [29].

The gaps measured in this study frequently exceeded **50 μm**, a threshold previously suggested as potentially limiting force transmission efficiency [56]. This finding underscores that current thermoforming methods may inherently restrict the precision of certain tooth movements. Studies by Krey *et al*. [43], Ryu *et al*. [57], and Lombardo *et al*. [58] all report significant reductions in material thickness at the gingival and incisal margins during thermoforming, which aligns with the larger gaps we observed in these regions. This non-uniform thinning of aligner material, particularly at areas of maximum draw, provides a mechanistic explanation for the regional variation in adaptation and emphasizes the limitations of current fabrication processes in achieving ideal contact at the aligner–attachment interface.

Comparison with previous research

The results of this study are consistent with earlier investigations on microscopic aligner adaptation, while also expanding on their findings. Mantovani *et al*. reported average gaps ranging from **22.7 to 80.1 μm** depending on the measurement location [26], which falls within the range observed in our study. Our analysis, however, identified a slightly wider range (**14.75–91.07 μm**), likely due to the inclusion of multiple attachment designs and the systematic assessment of several standardized points per attachment.

Lombardo *et al*. examined six different aligner brands using micro-computed tomography, reporting mean gaps of **24.3 to 48.9 μm** [28]. While these averages align with our mean measurements, their maximum values were lower than those recorded in our study. This discrepancy is likely due to methodological differences: micro-CT evaluates volumetric gaps, whereas SEM provides higher-resolution point-specific measurements, allowing detection of subtle variations in material-tooth adaptation. Both techniques offer valuable insights, but SEM enables precise assessment of localized discrepancies that may influence clinical outcomes.

Clinical relevance

The observed patterns of regional adaptation have direct implications for orthodontic treatment planning. Areas with better fit, such as flat buccal surfaces, may allow for more aggressive tooth movement, whereas regions with poorer adaptation, like gingival margins and sharp transitions, may require a more cautious approach. Clinicians may consider the following strategies to optimize treatment outcomes:

- Employing smaller incremental movements in stages where fit is limited;
- Adding supplementary attachments to distribute forces more evenly;
- Incorporating auxiliary mechanics such as elastics or temporary anchorage devices;
- Selecting multi-layer aligner materials for complex or high-stress movements;

- Prioritizing optimized attachment designs when available to improve contact and force transmission.

The finding that even the most favorable material–attachment combinations demonstrated notable gaps highlights intrinsic limitations in force delivery with current aligner systems. This may partly explain the variability in clinical outcomes, despite advances in digital treatment planning, AI-assisted analysis, and biomechanically optimized attachments [19, 59, 60].

Future perspectives

The consistent pattern of regional variation in adaptation suggests opportunities for technological improvements in aligner manufacturing. Current thermoforming techniques appear limited in achieving uniform contact across complex surfaces. Future approaches could include:

- Multi-stage thermoforming with targeted pressure application to reduce uneven stretching;
- Direct 3D printing of aligners to bypass limitations of traditional thermoforming [38];
- Development of shape-memory polymers with improved conformability;
- Hybrid manufacturing approaches combining thermoforming with localized reinforcement;
- Designing attachments specifically tailored to optimize fit in regions prone to poor adaptation.

Study limitations

Several limitations should be noted. The use of bovine teeth, while advantageous for standardization, may not fully replicate human enamel behavior [33]. The static nature of the measurements does not account for dynamic changes that occur in the oral environment, including temperature fluctuations, masticatory forces, and material fatigue. Additionally, SEM analysis, while offering high-resolution imaging, provides two-dimensional cross-sectional information and cannot fully capture three-dimensional variations around the attachment perimeter.

Future research should focus on simulating clinical conditions, evaluating adaptation under functional forces, and correlating microscopic measurements with actual treatment outcomes to better inform clinical decision-making.

Conclusion

The findings of this study indicate that current clear aligner systems and attachment designs do not achieve perfect fit at the microscopic level. Notable differences were observed between materials and attachment geometries, with multi-layer aligners and optimized attachments providing better adaptation. Patterns of regional variation were evident, with the largest gaps occurring at gingival margins and the smallest at flat tooth surfaces, offering partial mechanical explanations for movement-specific limitations in aligner therapy. However, clinical outcomes are also influenced by factors such as patient compliance, biomechanical complexity, treatment planning accuracy, and individual biological responses. These results highlight the importance of continued innovation in aligner materials and attachment design to improve force transfer and treatment predictability. Clinicians should integrate these adaptation insights with other clinical considerations when selecting materials, designing attachments, and planning treatment to set realistic expectations for tooth movement.

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