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Galaxy Publication

Electron Microscopic Evaluation of Attachment Design Compatibility in Clear Aligner Therapy

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ABSTRACT

The clinical effectiveness of clear aligners hinges on how accurately forces are transmitted through the interface between aligners and attachments. This study aimed to investigate the microscopic fit between two types of aligner materials—Duran+ and Zendura FLX—and two attachment designs, rectangular and optimized, using scanning electron microscopy (SEM). Fifty-six attachment–aligner samples were prepared and divided evenly into four groups: rectangular attachments with Duran+ (n = 14), rectangular with Zendura FLX (n = 14), optimized with Duran+ (n = 14), and optimized with Zendura FLX (n = 14). Attachments were bonded to bovine incisors following a standardized protocol, and aligners were thermoformed at 220 °C for 40 seconds. Cross-sections were examined under SEM at 250× magnification, and gaps between aligner and attachment were measured at multiple points (seven for rectangular, five for optimized). Gap sizes ranged from 14.75 ± 1.41 µm to 91.07 ± 3.11 µm. Zendura FLX exhibited significantly closer adaptation compared with Duran+ in rectangular attachments (42.10 ± 1.07 µm vs. 44.52 ± 1.51 µm, $p < 0.001$). Overall, optimized attachments achieved better microscopic fit than rectangular designs. Across all groups, the largest gaps were observed at gingival margins (67.18–91.07 µm), whereas the smallest were found on flat buccal surfaces (14.75–20.98 µm). Perfect contact between aligners and attachments was not observed for any combination. Both material type and attachment geometry play crucial roles in microscopic adaptation, with multi-layered aligner materials and optimized designs demonstrating superior conformity. These results provide insight into the mechanical reasons behind certain limitations in clinical clear aligner performance.

Keywords: Thermoforming, Orthodontic attachments, Clear aligners, Material adaptation, Scanning electron microscopy

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Introduction

The demand for orthodontic treatments that prioritize aesthetics has fueled the rapid adoption of clear aligner therapy [1, 2]. Since Kesling first introduced aligners in the 1940s, these devices have progressed from simple retainers to advanced appliances capable of executing complex tooth movements [3, 4]. This transformation has been driven by improvements in material science, digital workflows, and the incorporation of attachments—resin-based structures bonded to teeth that enhance force application and guide precise movement [5, 6].

Patients increasingly prefer clear aligners due to their cosmetic advantages, comfort, and superior hygiene maintenance relative to fixed braces [7, 8]. The integration of computer-aided design and manufacturing (CAD/CAM) has revolutionized aligner production [9, 10], while artificial intelligence now plays a role in comprehensive treatment planning, assessing facial aesthetics, and establishing optimal orthodontic objectives to improve outcomes [11]. Furthermore, direct 3D printing of aligners has emerged as a promising alternative to thermoforming, potentially overcoming the limitations of traditional manufacturing [12]. Advances in multi-layer aligner materials have enhanced mechanical performance and treatment precision [13], and the use of various attachment designs now allows movements once thought unattainable with removable appliances [14]. Biomechanical research confirms that attachment geometry improves force delivery [15, 16], while multi-layer materials provide superior strength and durability [13], together enabling more reliable orthodontic corrections.

Despite these technological developments, predictable tooth movement remains a challenge. Certain movements—such as extrusion, rotation, and root torque—demonstrate inconsistent outcomes [17-19]. Djeu *et al.* reported that while aligners perform similarly to fixed appliances in some respects, they are less effective in correcting buccolingual inclinations, occlusal contacts, and overall occlusion [20]. These limitations highlight the need to explore the mechanical factors underlying aligner performance.

A critical determinant of treatment efficacy is the efficiency of force transfer at the aligner–attachment interface [15,16]. Previous studies have shown that attachment design affects both force distribution and movement predictability [21, 22]. However, the microscopic interaction between aligners and attachments, which governs precise force application, remains insufficiently characterized. Various approaches, including tensile testing, silicone replica techniques, and optical scanning, have been used to evaluate aligner fit, but each carries inherent limitations [6, 23, 24].

Recent imaging-based studies have begun to clarify the complexity of this interface. Efforts to optimize fit have focused on novel materials and fabrication techniques [25]. Mantovani *et al.* utilized scanning electron microscopy to reveal gaps between aligners and teeth [26, 27], while Lombardo *et al.* employed micro-computed tomography to compare aligner brands, uncovering significant variations in interface gaps [28]. These findings suggest that precise microscopic adaptation may be essential for clinical success. Investigations into the clinical implications of gap dimensions indicate that 50 µm represents a critical threshold for compromised force transmission (Barone *et al.* [29]), gaps above 100 µm can reduce applied force by 40% (Elkholy *et al.* [30]), and gaps between 50–200 µm are considered clinically significant (Hahn *et al.* [31]), highlighting the necessity of accurate adaptation measurement.

The present study aimed to quantify microscopic adaptation at the aligner–attachment interface by examining two aligner materials (Duran+ and Zendura FLX) and two attachment configurations (rectangular and optimized) using scanning electron microscopy. The null hypothesis proposed that perfect adaptation (100 percent fit) occurs between aligners and attachments, independent of material type or attachment design.

Materials and Methods

Study design and sample size

An in vitro investigation was conducted to examine how two different aligner materials interact with two types of attachment designs at the microscopic level. Sample size calculations using G*Power 3.1 indicated that 56 specimens (14 per group) were needed to achieve 80 percent power at a significance level of $\alpha = 0.05$, based on a previously reported effect size of 0.46 for interfacial gap measurements [32].

Specimen selection and preparation

Fifty-six bovine mandibular incisors, exhibiting intact enamel, uniform crown dimensions, and free of structural defects, were selected in line with standard dental research practices [33, 34]. Bovine teeth were chosen due to their availability and bonding characteristics similar to human enamel. After cleaning with pumice, the teeth were stored in distilled water at room temperature until use. Each tooth was embedded in cold-cure acrylic resin to facilitate handling and then digitally scanned using a high-precision 3D scanner (3Shape E1 Series, Copenhagen, Denmark) with an accuracy of 7–10 µm [35]. To ensure uniformity across all specimens, a single trained operator (C.S.) performed all procedures including mounting, attachment placement, aligner fabrication, and sectioning, eliminating inter-operator variability.

Design and fabrication of attachments

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

• Rectangular: 3 mm × 5 mm × 2 mm
• Optimized: 3 mm × 5 mm × 2.5 mm with curved surfaces

These dimensions reflect common clinical practice and are supported by prior literature [6, 21]. The templates incorporated a 0.1 mm offset [36] and were designed with a 2 mm thickness to balance flexibility and rigidity, based on material testing data [37]. Templates were produced using a Form 3 3D printer (Formlabs, Somerville, MA, USA) with IBT resin at 0.1 mm layer resolution. The resin's flexural modulus of 2.2 GPa allowed the template to conform to the convex contours of the teeth while maintaining dimensional accuracy during composite application. Additional design modifications, such as extended margins and flexible borders, enhanced marginal adaptation. Each template was trialed on its corresponding tooth model to verify full fit before clinical simulation. Post-processing included a 20-minute wash in 99 percent isopropyl alcohol followed by UV curing at sixty degrees Celsius for sixty minutes [38].

Figure 1 illustrates the workflow from digital design to template fabrication, providing a visual overview of the steps involved in creating standardized attachment templates.

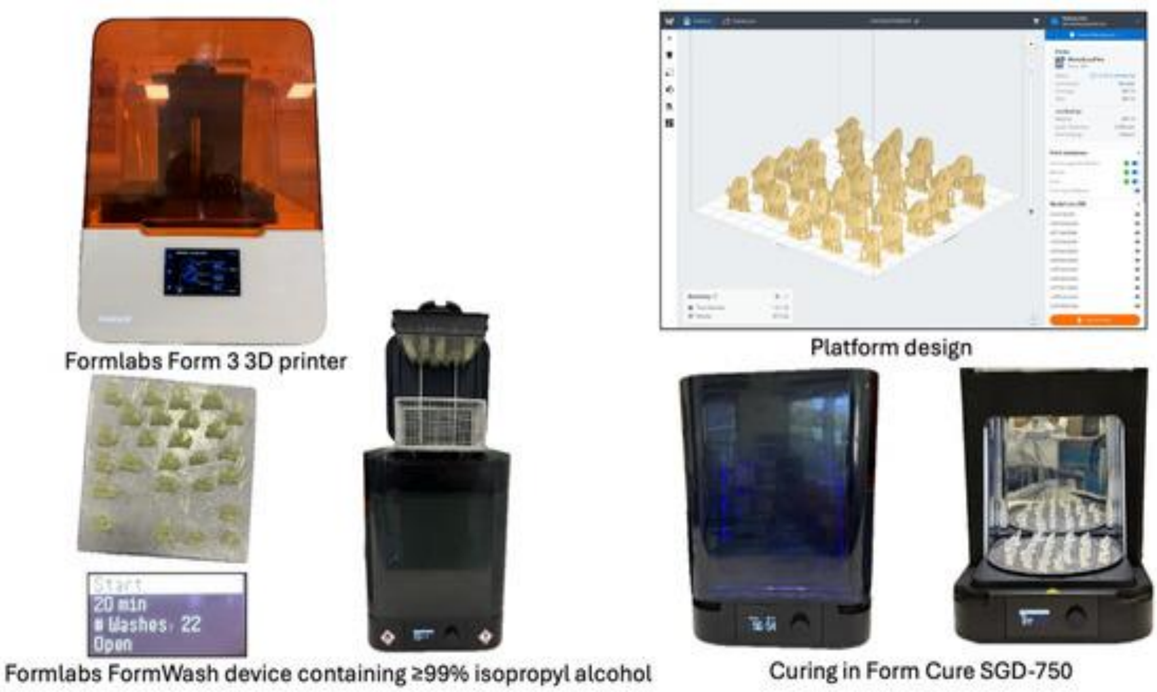

Figure 1. Attachment template production chart

Attachment bonding procedure

All specimens underwent a standardized bonding workflow to ensure consistency. Enamel surfaces were first etched with 37 percent phosphoric acid for thirty seconds [39], followed by application of Transbond XT Primer (3M Unitek, Monrovia, CA, USA) [40]. The bonding agent was light-cured for twenty seconds using a Woodpecker Dental iLed device (Guilin, China). Composite material (Transbond XT, 3M Unitek) was then placed within the attachment template, which was seated onto the tooth under a controlled 50 g force measured with a Dentaurum force gauge. The composite was cured for forty seconds [41]. Once the template was removed, any excess material was meticulously trimmed under magnification to preserve smooth margins without altering the planned attachment shape.

Attachments were consistently located at the center of the buccal surface, four millimeters from the incisal edge, guided by a digital template. A custom sectioning jig ensured that all teeth were cut at identical angles through the attachment center.

Aligner fabrication

Two aligner types were evaluated for their fit:

• Duran+ (Scheu Dental, Iserlohn, Germany), a 0.76 mm single-layer PETG sheet;

- Zendura FLX (Bay Materials, Fremont, CA, USA), a 0.76 mm multi-layer polyurethane with an elastomeric core.

Duran+ exhibits a flexural modulus of 2200 MPa, whereas Zendura FLX's multi-layer design reduces the modulus to 1100 MPa, enhancing flexibility. These materials were chosen due to their widespread clinical application and contrasting mechanical properties [42, 43]. Each aligner was thermoformed individually over its respective mounted tooth to avoid inconsistencies inherent to group thermoforming. The Biostar device (Scheu Dental) was used at 220 degrees Celsius for forty seconds under ≥4 bar pressure, following the manufacturers' instructions [44]. No spacer foils were employed to allow direct assessment of material adaptation, and aligners were trimmed two millimeters beyond the gingival margin according to standardized protocols [45].

SEM sample preparation and analysis

To examine the aligner–attachment interface microscopically, teeth were sectioned buccolingually with a precision cutting machine (Saeshin Strong 210, Daegu, Republic of Korea) using a diamond-embedded disc (Acurata GmbH, Thurmansbang, Germany) under continuous water cooling to prevent heat-induced deformation [46]. Prior to cutting, samples were embedded in cold-cure epoxy resin to provide support and preserve interface integrity. Sectioning was performed at 500 rpm with minimal pressure to reduce compression artifacts. Light microscopy inspection confirmed that the interface remained intact without observable separation or distortion. **Figure 2** depicts a representative cross-section prepared for scanning electron microscopy.

Figure 2. Cross-sectioned tooth sample

Gold-palladium coating was applied to the cross-sectioned specimens using a Leica EM ACE600 sputter coater (Wetzlar, Germany) to optimize imaging resolution [47, 48] **(Figure 3)**.

Figure 3. Coating tooth samples

The samples were observed using an EVO 40 Series scanning electron microscope (Carl Zeiss AG, Jena, Germany) under conditions of 15 kV accelerating voltage, ten millimeters working distance, and 250× magnification [49].

Gap evaluations were carried out at designated sites:

• Rectangular attachments: measurements taken at 7 standardized points **(Figure 4)**

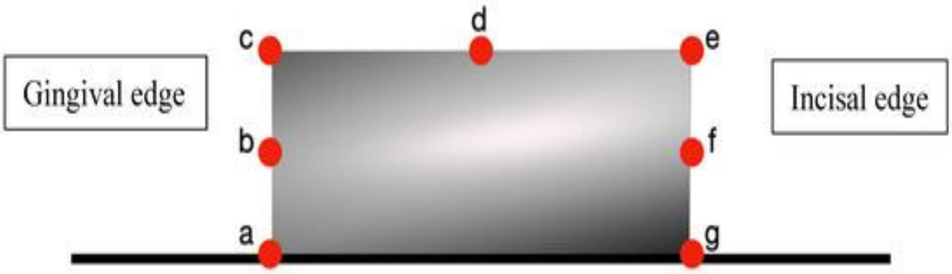

Figure 4. Seven points measured on the rectangular attachment

The measurement points on rectangular attachments, shown in **Figure 4**, were defined as follows: (a) gingival border—where the aligner meets the tooth at the gingival margin, (b) gingival midpoint—central area of the gingival surface, (c) gingival angle—corner between gingival and buccal surfaces, (d) buccal midpoint—center of the buccal surface, (e) occlusal angle—junction of buccal and occlusal surfaces, (f) occlusal midpoint—middle of the occlusal surface, (g) occlusal border—where the aligner contacts the tooth at the occlusal margin.

• For optimized attachments, measurements were recorded at five predetermined points **(Figure 5)**.

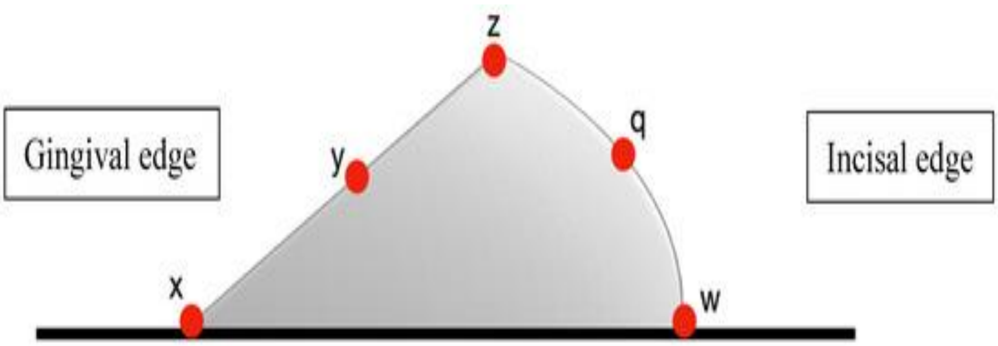

Figure 5. Five points measured on the optimized attachment

Figure 5 depicts the designated measurement points on optimized attachments: (x) gingival border—site of the aligner–tooth junction at the gingival margin where gaps are typically largest, (y) gingival midpoint—central portion of the curved gingival surface evaluating adaptation to the beveled profile, (z) buccal angle—critical junction between the attachment apex and tooth surface, (q) occlusal midpoint—middle of the gentle occlusal slope, and (w) occlusal border—aligner–tooth contact at the occlusal edge. The reduction to five points (from seven in rectangular attachments) reflects the smoother geometry and absence of sharp transitions in the optimized design.

Measurement locations were purposefully chosen to reflect regional variations in thermoformed aligner fit, spanning the gingival, middle, and occlusal thirds of the clinical crown. Criteria for selection included: (1) areas prone to maximum stress based on attachment shape, (2) transitional zones linking attachment and tooth surfaces, and (3) consistent positions along the gingival–occlusal axis to allow inter-group comparison. The seven points on rectangular attachments were necessary to capture all geometric irregularities, whereas the streamlined contours of optimized attachments could be adequately characterized with five targeted sites.

All measurements were taken by a single calibrated examiner who was blinded to group assignment. **Figure 6** presents representative SEM images at 250× magnification demonstrating the measurement approach.

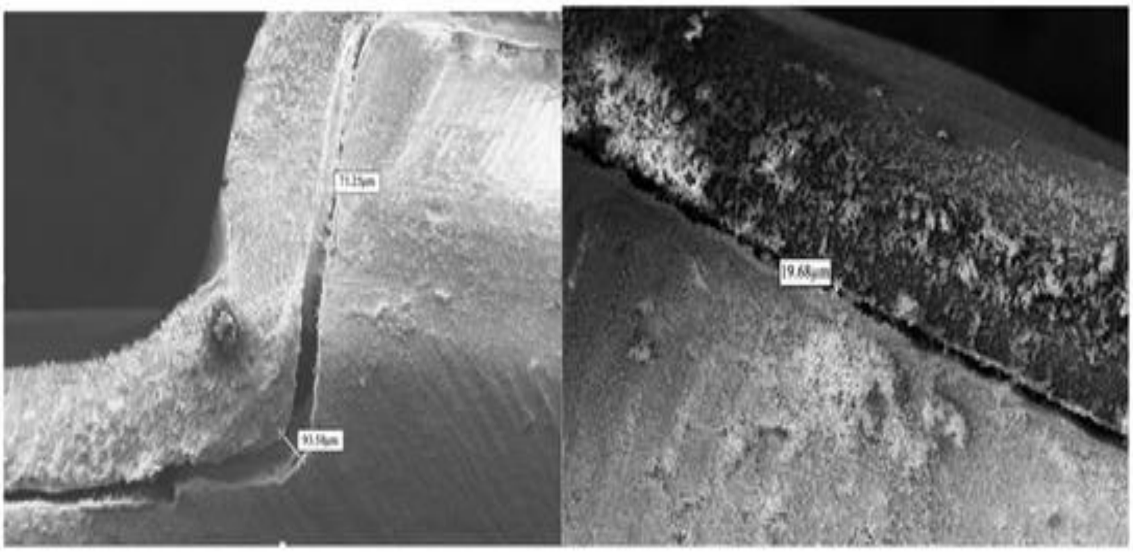

Figure 6. SEM images measurements (Mag = 250×)

Following consultation with biostatistics experts, a single-examiner protocol was implemented because the main outcome—gap measurements—was based on objective digital readings using SmartSEM version 6.0 (Carl Zeiss AG) rather than subjective judgment. The examiner's task was limited to locating predefined anatomical landmarks and triggering software-based measurements. Reliability was ensured through strict standardization, which included: (1) detailed photographic references for each measurement site, (2) automated SEM measurement functions to remove manual variability, and (3) excellent intra-examiner consistency (ICC > 0.95). To prevent bias, the examiner remained blinded to group allocation. An independent researcher randomly coded SEM images, with the key kept sealed until all analyses were completed; the examiner recorded measurements using only these coded images, and group identity was revealed afterward.

Statistical analysis

Data were processed in SPSS version 24.0 (IBM Corp., Armonk, NY, USA). The Shapiro–Wilk test evaluated data normality, and, due to non-normal distribution, the Mann–Whitney U test was applied for inter-group comparisons. Results are presented as mean ± standard deviation, with significance defined at $p < 0.05$.

Results and Discussion

Gap sizes were influenced by measurement site, attachment type, and aligner material, and no sample achieved complete adaptation, as all showed measurable gaps at every point.

Material comparison

In rectangular attachments, Zendura FLX exhibited significantly better fit than Duran+ at multiple measurement sites **(Table 1)**, with mean gap distances of 42.10 ± 1.07 µm for Zendura FLX versus 44.52 ± 1.51 µm for Duran+ ($p < 0.001$). Significant differences were detected at the gingival border ($p = 0.001$), gingival midpoint ($p = 0.022$), gingival angle ($p = 0.023$), and occlusal border ($p = 0.006$).

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 ± 2.611	17.62 ± 2.49	0.206
g (Occlusal border)	43.70 ± 4.123	38.41 ± 3.40	0.006 *

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

For optimized attachments, the variation between materials was minimal, with a significant difference observed only at the buccal angle **(Table 2)**. Overall, the mean gap distances 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 ± 2.831	16.50 ± 2.96	0.122
w (Occlusal border)	47.28 ± 4.07	45.50 ± 3.93	0.248

* $p < 0.05$.

Attachment design comparison

Regardless of the aligner material, optimized attachments exhibited improved fit compared with rectangular attachments **(Table 3)**. For Duran+ aligners, the mean gap was reduced to 39.41 ± 3.20 µm with optimized attachments, compared to 44.52 ± 1.51 µm for rectangular ones. Similarly, Zendura FLX aligners showed smaller average gaps with optimized attachments (37.30 ± 3.09 µm) versus rectangular attachments (42.10 ± 1.07 µm).

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

** $p < 0.001$.

Regional variation patterns

Clear trends in gap distribution were observed across all groups. Ignoring the type of aligner material, rectangular attachments exhibited notable regional differences **(Table 4)**.

Table 4. Gap measurements without considering material classification in rectangular attachment (n = 28)

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

Regional variation patterns

Gap measurements revealed a consistent distribution trend across all groups:

- The largest gaps were located at the gingival borders (67.18–91.07 μm);
- Intermediate gaps were present at the occlusal borders (38.41–47.28 μm);
- The smallest gaps occurred on flat surfaces and sharp angles (14.75–20.98 μm).

The findings quantitatively confirm that current materials and manufacturing methods do not achieve perfect adaptation between clear aligners and attachments. All tested combinations exhibited measurable gaps ranging from 14.75 μm to 91.07 μm, highlighting limitations in force transmission efficiency and clinical constraints in aligner therapy.

Influence of material properties on adaptation

Zendura FLX demonstrated better conformity compared with Duran+, supporting previous evidence that material characteristics influence aligner fit [50, 51]. Its multi-layer construction, with an elastomeric core between rigid outer layers, enhances adaptation to complex attachment geometries. This is consistent with Cowley *et al.*, who reported an 8–12% higher retention for multi-layer materials relative to single-layer ones [45]. The observed 5.5% improvement in adaptation for Zendura FLX on rectangular attachments indicates that material choice can significantly impact force application efficiency.

The material effect was more pronounced in rectangular attachments than in optimized ones, suggesting an interaction between attachment geometry and material behavior. Sharp angles in rectangular attachments challenge material conformity, whereas optimized attachments' smoother contours facilitate better adaptation. Ryokawa *et al.* also reported that material composition significantly affects stress distribution, relaxation, and dental surface adaptation [50], corroborating our findings of material-dependent adaptation patterns.

Implications of attachment design

Optimized attachments achieved roughly 11.5% improved adaptation over rectangular designs. Beyond gradual contours, these attachments incorporate design elements such as optimized force vectors, variable thickness, movement-specific orientation, and strategic undercuts for retention. The superior fit likely results from a combination of smooth surface transitions allowing better material flow during thermoforming and biomechanically optimized shapes promoting favorable stress distribution. This multidimensional design approach extends the work of Savignano *et al.*, who demonstrated the significant effect of attachment geometry on force systems [21].

It is important to distinguish that our study measured microscopic gaps at the aligner–attachment interface rather than retention forces. While both parameters are clinically relevant, they assess different aspects of aligner performance. Interestingly, our results differ from Dasy *et al.*, who found higher retention with rectangular attachments [6]. This discrepancy emphasizes the difference between retention, which measures the force required to remove an aligner, and adaptation, which evaluates contact precision for efficient force transmission. Adequate adaptation can mitigate lower retention by improving force delivery, potentially explaining the clinical preference for optimized attachments despite contrasting retention data.

However, optimized attachments also have documented limitations. They do not consistently outperform conventional attachments for all movements, with both types often achieving only partial planned movement and sometimes requiring overcorrection [52]. Additionally, optimized root control attachments are more prone to wear over time, particularly after four months, leading to greater performance degradation compared with rectangular attachments [53]. This wear may affect long-term treatment outcomes, especially during canine distalization, and may necessitate rebonding or restoration during therapy.

Current studies indicate that attachment effectiveness varies depending on the specific tooth movement, and no single design consistently outperforms others. Optimized attachments are most effective for lateral incisor rotation [54], while vertical attachments are better suited for mesio-distal angulation, and horizontal attachments perform best for vestibulo-lingual (torque) adjustments [54]. For maxillary lateral incisor extrusion in the 0.3–2.5 mm range, horizontal attachments have shown superior performance compared with optimized designs [55]. Rectangular attachments tend to maintain higher long-term efficiency for canine distalization because they are less affected by surface wear [53]. These observations underscore the importance of customizing attachment selection based on the intended movement and considering both short-term performance and durability.

Regional variation and clinical implications

This investigation specifically examined how thermoformed aligner adaptation varies across different regions of the clinical crown by measuring at gingival, middle, and occlusal locations. This approach is consistent with Krey *et al.* [43], who reported uneven aligner thickness, with reductions of up to 50% near gingival margins. Our measurements confirmed this trend, revealing the largest gaps at gingival borders (67.18–91.07 µm) and smaller gaps at occlusal areas (38.41–47.28 µm).

The observed regional differences provide insight into why some movements are less predictable. The greatest gaps at gingival margins may limit the effectiveness of extrusive movements, as noted by Rossini *et al.* [17], which rely on forces applied near the gingiva. In contrast, smaller gaps along flat buccal surfaces may enhance movements that depend on direct aligner–tooth contact. Simple tipping motions often do not require attachments because the aligner can apply sufficient force above the tooth's center of resistance [56], whereas complex movements, such as bodily translation or root torque, require precise attachment-mediated force delivery [29]. Thus, regional adaptation patterns help explain variability in movement predictability without suggesting attachments are necessary for all movements.

Gap measurements in our study exceeded the 50 µm threshold suggested by Barone *et al.* [57] for optimal force transfer, indicating that current manufacturing processes may inherently restrict certain movements. The regional differences appear to result from non-uniform material stretching during thermoforming. Krey *et al.* [43] reported up to 50 percent thickness loss at gingival margins, while Ryu *et al.* [58] observed reductions of up to 70 percent at incisal edges and 50 percent at gingival margins. Lombardo *et al.* [59] also documented substantial thinning at cusp tips and marginal areas, with these changes correlating with gap formation. The largest gaps at gingival margins (67.18–91.07 µm) can be explained by this differential material thinning during thermoforming, which is most pronounced in areas with the greatest draw depth.

Comparison with previous studies

Our observations are in line with previous research on aligner adaptation while offering additional insights. Mantovani *et al.* reported mean gaps ranging from 22.7 to 80.1 µm depending on location [26], which overlaps with our measurements, though our range (14.75–91.07 µm) was broader, likely due to evaluating multiple attachment types at several standardized points.

Lombardo *et al.*, using micro-CT to assess six aligner brands, found mean gaps between 24.3 and 48.9 µm [28]. While their averages are similar to ours, the maximum values in our study were higher, probably reflecting methodological differences: micro-CT provides volumetric measurements, whereas SEM allows high-resolution point-specific evaluation, capturing finer variations in adaptation.

Clinical implications

These findings have practical relevance for treatment planning. The regional differences in fit suggest that clinicians should consider the site-specific efficiency of force transmission. Movements involving regions with better adaptation, such as flat surfaces, may be planned more aggressively, whereas movements relying on areas with larger gaps, like gingival margins or sharp angles, may require:

- Smaller incremental steps for safer staging;
- Additional attachments to distribute forces;
- Auxiliary devices, such as elastics or temporary anchorage;
- Use of multi-layer aligner materials for complex movements;
- Preference for optimized attachment geometries when available.

Even the most favorable material–attachment combinations exhibited measurable gaps, which may partly explain the persistence of unpredictable movements despite advanced planning software, AI-assisted systems, and biomechanically optimized attachments [19, 60, 61].

Future directions

The repeated pattern of regional variation points to areas for improvement in aligner manufacturing. Current thermoforming methods appear limited in achieving uniform adaptation across complex shapes. Future strategies may include:

- Multi-stage thermoforming with region-specific pressure;
- Direct 3D printing of aligners to bypass thermoforming limitations [38];
- Development of shape-memory or highly adaptive materials;
- Hybrid manufacturing approaches combining thermoforming with selective reinforcement;
- Attachment designs tailored to regional adaptation characteristics.

Study limitations

Several limitations should be noted. Bovine teeth were used to standardize samples, but they may not fully replicate human enamel [33]. The static nature of this evaluation does not account for intraoral dynamics such as forces, temperature changes, or material fatigue. SEM provides high-resolution two-dimensional measurements at specific locations but cannot capture the three-dimensional variation around attachment perimeters. Future research should simulate clinical conditions and link microscopic adaptation to actual treatment outcomes.

Conclusion

Perfect adaptation between clear aligners and attachments is not achieved with current materials and fabrication methods. Differences exist between materials and attachment designs, with multi-layer aligners and optimized attachments showing superior microscopic fit. Regional variation—largest gaps at gingival margins and smallest at flat surfaces—helps explain movement-specific limitations in aligner therapy. Clinical outcomes depend on multiple factors, including patient compliance, biomechanical complexity, treatment planning, and individual biological response. These findings highlight the need for further refinement of aligner materials and attachment designs to improve force transfer and treatment predictability, and they suggest that clinicians should consider adaptation patterns when planning tooth movement and setting realistic expectations.

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