Review Article

Attachments in Clear Aligner Orthodontic Therapy: An In-depth Review

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Abstract

Clear aligner therapy has transformed the landscape of orthodontic treatment by offering patients a discreet, comfortable, and effective alternative to traditional fixed appliances. However, clear aligners alone have mechanical limitations that challenge their ability to achieve complex dental movements such as rotation, extrusion, and torque. To address these shortcomings, composite attachments have become an essential component of aligner-based therapy. These attachments improve aligner retention and force delivery by serving as force modifiers or directional aids, enabling the aligners to exert more effective and predictable pressures on the teeth. This comprehensive review explores the types, biomechanics, clinical implications, esthetic challenges, and future innovations related to attachments in clear aligner orthodontic therapy. Drawing from multiple academic studies and clinical trials, the review highlights the integral role attachments play in enhancing aligner performance and treatment outcomes.

Keywords: Aligners, Attachments, Clinical effectiveness, Orthodontics, Position, positioning, Tooth movement.

Introduction

The advent of clear aligner systems has revolutionized orthodontics, particularly for patients seeking a more esthetic and comfortable experience compared to conventional metal braces. Initially designed for minor relapses and simple dental movements, the scope of aligners has expanded dramatically with the integration of digital planning and auxiliary tools. Among these, composite attachments have become the most widely adopted auxiliary mechanism to augment aligner capabilities.

These attachments – small, often invisible bumps of composite material – are strategically placed on tooth surfaces to enhance the aligner's grip and control over movement. By increasing the contact surface and changing the vector of applied forces, attachments allow for more precise and efficient execution of treatment plans.[1] Understanding their biomechanics, classification, clinical application, and limitations is vital for clinicians who seek to optimize aligner therapy outcomes.

Historical Evolution and Technological Advances

The idea of removable orthodontic appliances dates back to Kesling's introduction of tooth positioners in the 1940s. The evolution continued with Ponitz's vacuum-formed retainers in the 1970s, which laid the groundwork for modern clear aligners.[2] In 1999, the launch of Invisalign introduced a fully digital approach to orthodontics, enabling customized treatment plans through computer-aided design/computer-aided manufacturing technologies.

Early aligners lacked the capability to handle complex movements, which led to unpredictable outcomes. The addition of attachments – initially rudimentary – marked a significant milestone. With the advancement of intraoral scanning, three-dimensional (3D) printing, and force simulation software, today's attachments are meticulously designed to target specific movements with increased precision. Their shapes, sizes, and placements are now customized using treatment planning software, contributing to higher levels of control and predictability.

Classification of Attachments

Attachments are broadly categorized into two main types based on design and placement methodology:

Access this article online

Website:
www.jrad.co.in

DOI:
https://doi.org/10.53064/jrad.2024.16.5.724

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Received: Aug. 08, 2025; **Accepted:** Sep. 01, 2025; **Published:** Sep. 09, 2025

How to cite this article: Urade N, Mongia JP, Sthapak R, Jai VA, Sadhu AK, Kawana P. Attachments in Clear Aligner Orthodontic Therapy: An In-depth Review. J Res Adv Dent 2025;16(5):1-5.

1. Conventional Attachments
    - Rectangular (horizontal and vertical): These are commonly used for extrusion and rotation
    - Beveled: Useful for torque and sliding movements
    - Ellipsoid: Applied when a smoother interface is needed for force redirection.
2. Optimized Attachments
    - Designed by software algorithms such as ClinCheck
    - Tailored to the biomechanical needs of each tooth
    - Often irregular in shape with multi-planar surfaces.

Attachments and Aligner Modifications

Some of the limitations of aligner therapy are connected to the removable nature of the appliance as well as the common shape-driven method for correcting dental malpositions with aligners. Further development and improvement of aligners addressed these limitations by the implementation of composite attachments and local aligner reinforcements, which may be regarded as modifications of the appliance's simple basic form. It is important to note that both the knowledge of the mechanisms and the awareness of insufficiencies inherent in these modifications are crucial for realistic treatment planning and the achievement of the treatment goals.

While optimized attachments rely on AI-driven analysis of force vectors and movement simulations, conventional attachments are chosen and positioned by the orthodontist. Each type serves specific roles in the treatment of complex malocclusions.

In general, composite attachments and local aligner reinforcements can be classified according to their functions.[3]

1. Movement attachments and specific aligner reinforcements may increase the efficacy of the target movement and aim at widening the spectrum of achievable tooth movement types
2. Specific movement attachments eliminate or minimize undesired collateral movement components
3. Retention attachments are used to prevent the dislodgement of the appliance
4. Auxiliary attachments enable external force application.

Movement Attachments

According to a fundamental physical principle, two contacting surfaces always generate opposed contact force vectors with an orientation orthogonal to the contact interface. The application of this principle to aligner therapy means that efficient tooth movement with aligners crucially benefits from aligner–tooth contact surfaces with an orientation perpendicular to the desired movement direction. If such surfaces are scarcely available, they are to be artificially extended in the form of composite attachments. This is exemplified by the rectangular attachments recommended for molar distalization (Figure 1).

If a molar equipped with such an attachment is displaced distally in the setup, intraoral seating of the aligner generates a distally directed contact force at the attachment's mesial surface. As explained, such eccentric force application induces tipping of the molar; conversely, bodily movement consisting of both crown and root movement requires a counter-moment in the same plane in space. Since for molar distalization a force of ca. 1 N is to be applied at a distance of approximately 10 mm from the CR, a counter-moment of ca. 10 N mm is needed. It has to be noted that a contact force couple in the range of 2–3 N applied to the mesial and distal attachment regions (Figure 1a) is required to generate such a moment magnitude. From the practical aspect, this might be challenging, because aligners are made of relatively thin, thermoplastic polymers showing combined elastic and plastic deformation during application of such relatively high and very locally acting contact forces. An experimental study on this issue revealed that aligners with such attachments may actually generate an uprighting moment of 8.8 N mm, which is almost reaching the required magnitude.[4]

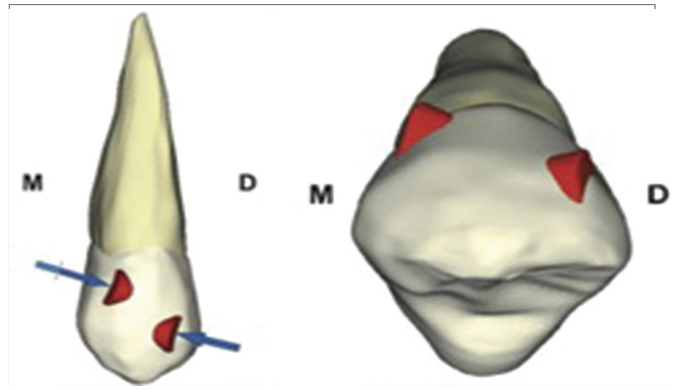

Figure 1: Rectangular movement attachment improving force application for molar distalization. Mesial (M) and distal (D) directions are indicated. (a) Buccal view. (b) Occlusal view. The beveled edge of the attachment's active mesial surface facilitates its engagement in the corresponding recess of the aligner, which is important to maintain movement control. This attachment type may also generate a force couple consisting of two contact forces at the occlusal and cervical attachment surfaces (arrows), which counteract the distal tipping of the crown, at least to a certain extent

Nevertheless, predominant tipping of molars has actually been observed in clinical studies examining molar distalization using the Invisalign system[5] or space closure by molar mesialization with aligners[6] if the achieved movements are properly separated in their translational and rotational (i.e., tipping) components. Such apparent inability of aligners to reliably create pure bodily movements is most likely related to local deformation as described earlier, and/or their dislodgement from the attachments.

Biomechanics and Force Distribution

Biomechanically, aligners function by applying pre-programmed forces through elasticity and material tension. Attachments enhance this function by serving as anchorage points that increase the aligner's effectiveness. They shift the location of force application closer to the tooth's center of resistance, resulting in more controlled and efficient movement.[7]

Finite element analysis[1] studies, such as the one conducted by Sultanoglu *et al*., offer quantitative validation of these effects. Their findings revealed that bucco-lingually placed rectangular attachments exerted higher stress in the periodontal ligament and enabled more pronounced tooth displacement – particularly effective in rotational correction of premolars.

The design and placement of attachments directly influence stress distribution and root trajectory. For example, horizontal attachments placed in the middle third of the crown are effective for extrusions, while vertical rectangular attachments promote mesiodistal movement and torque.

The counter-moment needed for mesiodistal translational movement of a canine or premolar may be generated by so-called couple attachments consisting of two subcomponents (Figure 2). This type allows a slightly greater distance between opposing force vectors, which may increase the counter-moment magnitude as well. The latter assumption seems to be confirmed by a finite-element study in which nearly bodily canine distalization could be achieved by use of such couple attachments when combined with class II elastics.[8]

Another example of a frequently implemented movement attachment is the type used for the derotation of canines and premolars, respectively (Figure 3).

This attachment may be regarded as a specific type because it has two functions. First, similar to the rectangular movement attachment for molars, it provides an effective surface for the mesially or distally directed force component; as it has a more buccal location with respect to the CR, it creates both a force and a moment component, leading to mesiodistal movement and mesiodistal rotation, respectively. Its second function is related to the observation that canines or premolars are often "slipping out" of the aligner during derotation, which is also described as the "melon-seed effect."[9]

This phenomenon describes the (most often undesired) collateral intrusive movement during derotation. It results from the fact that, due to the wedge-shaped crown surface, contact forces show oblique directions comprising both a horizontal and vertical vector component. The effectiveness of such attachments for canine or premolar derotation was tested in a recent comparative biomechanical *in vitro* study, demonstrating that a specific design similar to the optimized attachment incorporated in the Invisalign system has superior properties with regard to both the derotational effect and the minimization of collateral intrusion.[10]

Hence, it might be speculated that such improved attachment designs may also achieve higher clinical efficacy.

Principally, collateral intrusion may also be observed during derotation of incisors, especially in more peg-shaped maxillary lateral or mandibular incisors. Hence, a few general rules must be respected for derotation of incisors with aligners: first, attachments with extrusive active surfaces should be implemented to counteract the collateral intrusive force component (if intrusion is actually not required); second, planned rotational movements should be overcorrected due to the limited efficacy of aligners and high relapse tendency of derotations.[10]

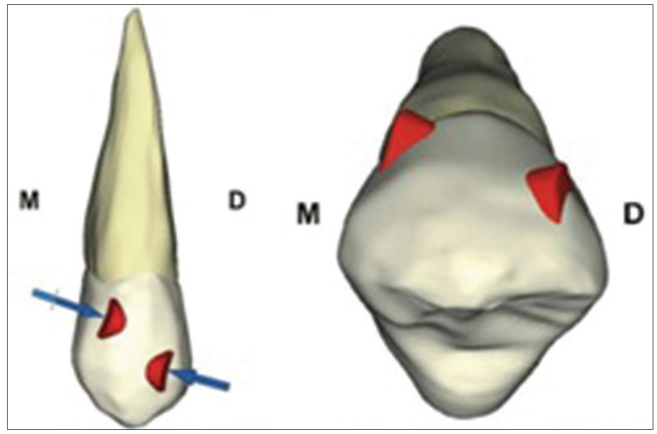

Figure 2: Couple attachment implemented for generating a counter-moment during mesiodistal translation of a canine. This configuration is designed for canine distalization, indicated by the longer force vector applied at the mesial attachment component. Mesial (M) and distal (D) directions are indicated. (a) Labial view. (b) Occlusal view. The counter-moment magnitude may be increased by the somewhat larger distance between the two contact force vectors

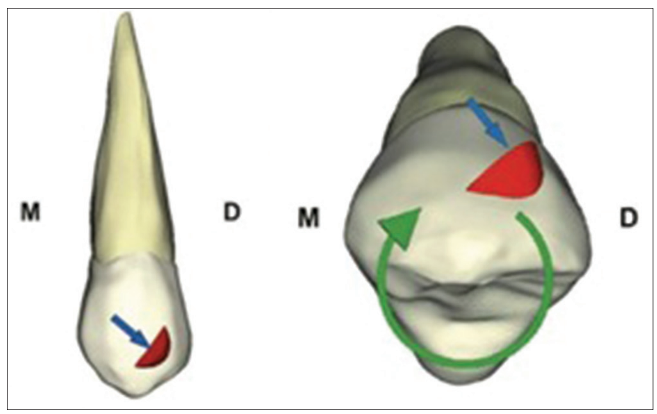

Figure 3: Optimized derotation attachment (which means distorotation in this example). The specific design may increase the efficacy of the targeted derotational moment and minimize or eliminate the collateral intrusive force. Mesial (M) and distal (D) directions are indicated. (a) Labial view. (b) Occlusal view. The derotational moment (green) is due to eccentric force application in the horizontal plane

Wedge-shaped movement attachments enable the extrusion of teeth due to their oblique active surface, which induces an oblique contact force comprising a vertical force component (Figure 4).

Both the flat angle between the attachment's active surface and the labial crown surface, and its relatively large active surface, ensure that the attachment sufficiently contacts the corresponding recess in the aligner. Nevertheless, patients have

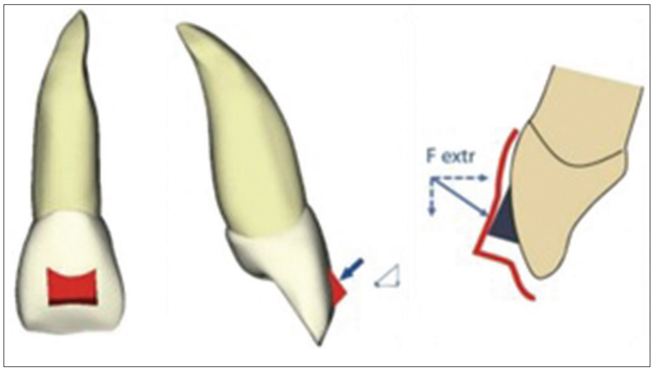

Figure 4: (a) Wedge-shaped movement attachment for extrusion. (b) The attachment's oblique active surface generates a contact force that may be subdivided into a vertical (extrusive) and horizontal force component. (c) Schematic drawing of the imperfect aligner-attachment fit

to be instructed to carefully monitor the aligner's fit between control sessions. Furthermore, silicone bite auxiliaries may help to maintain a good seating of the aligner. These rules generally apply to all attachment types.

Retention Attachments

The retention of an aligner is ensured – at least to a certain extent – by extending the appliance to the cervical crown regions, providing undercuts. The fact that most often only slight undercuts are present in a natural dentition may limit the aligner's resistance to being dislodged during wearing. This is especially true if vertical target or collateral force components have to be absorbed by adjacent teeth or tooth segments, respectively. For instance, if the frontal segment has to be intruded, a corresponding reactive, extrusive force is applied to the buccal segments. Since premolars and molars usually have relatively short clinical crowns with fewer undercuts, an aligner without any retentive auxiliaries could easily dislodge (particularly with larger activation steps). As a result, the aligner would also be ineffective with regard to the planned frontal intrusion. Hence, implementation of retention attachments on all premolars and molars, such as ellipsoid types, is strongly recommended in this situation.

Another reason why the aligner retention is of utmost importance is to ensure that the contact forces have adequate magnitudes, directions, and locations to keep tooth movements under control. It is important in this respect to consider both the absorption of reactive targets and undesired collateral forces. For example, lingual tipping of a lateral incisor parallel to the derotation of the adjacent canine might be ineffective without considering a retention attachment on the lateral incisor, as well.

The implementation of multiple retention attachments, however, may also increase the pull-off force of the aligner too much. Hence, these attachments must not be unnecessarily overdimensioned, which means that their prominence usually should be kept below 1 mm.[9]

Aligner Reinforcements

The requirement of a counter-tipping moment does not only apply to bodily movement in the mesiodistal direction, but also in the labiolingual or bucco-oral direction. Real incisor root torque (e.g., needed for correction of Class II Division 2 malocclusion) is characterized by a predominant or even pure root movement, which is even more challenging. In general, root movements in labiopalatal and buccolingual directions, respectively, require the reinforcement of the aligner at its cervical margin. Such modification may increase the resistance of an aligner against bending up of its U-form, which is important for creating an appropriate counter-tipping moment in the sagittal plane. Such reinforcements, named "power ridges," were first introduced in the Invisalign system.[11] Although it is propagated that reinforcement of the aligner's cervical margin may eliminate the tipping component during planned bodily movement or root torque of incisors, convincing evidence for this assumption based on clinical studies is still lacking. More specifically, careful interpretation of the results from a corresponding study reveals that the power ridges implemented in the Invisalign system seem not to be effective enough to reliably achieve a predominant incisor root movement in the palatal direction.[12] It is important in this context to make a clear distinction between real root torque and inclination correction by means of predominant crown movement; it is precisely in this respect that clinical studies evaluating therapeutic labiolingual incisor movements are often not sufficiently precise.

Auxiliary Attachments

Correction of a mild Class II or Class III relationship may be accomplished by intermaxillary forces provided by elastics. Retention of such auxiliaries may be accomplished either directly, using composite buttons bonded to the teeth, or indirectly by implementing buttons in the aligner using special pliers (in the molar region) or cutouts to hook the elastic (e.g., in the cervical region of the canine). If elastics with indirect retention are planned during aligner treatment, attention should also be paid to the enhancement of the retention of the appliance, which often requires several retention attachments.

Clinical Application in Orthodontic Movements

Attachments play an important role in achieving various types of tooth movements,[13] including:

- Extrusion: Aligners alone are poor at achieving vertical movements. Rectangular horizontal attachments improve engagement for extrusion, especially in anterior teeth
- Rotation: Particularly for round teeth such as canines and premolars. Dual-surface attachments or optimized designs enhance rotational control
- Torque: Vertical beveled attachments apply directed force for root movements
- Translation: Requires broad contact and increased retention; multi-surface attachments can aid bodily movement.

Proper attachment placement is critical for these movements to succeed. Malpositioned attachments may hinder the aligner's fit and reduce treatment efficiency.

Conclusion

Attachments have become indispensable tools in clear aligner therapy, bridging the gap between aligner limitations and complex orthodontic movements. Their role extends beyond mere mechanical aids – they serve as customized force delivery systems that significantly enhance treatment precision, predictability, and efficiency. As digital orthodontics continues to evolve, the development of optimized attachments based on biomechanical algorithms and individual tooth morphology has elevated the potential of aligner systems to rival traditional fixed appliances in treating complex malocclusions.

However, the success of these attachments depends heavily on accurate design, precise placement, and clinician experience. Future advancements, including AI-driven simulations, smart materials, and 3D printing, promise even greater personalization and control in treatment planning. Continued research and clinical validation will further solidify the role of attachments as critical components in achieving optimal outcomes in clear aligner orthodontics.

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