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Original Article

From Programmed Aligner Displacement to Periodontal Tissue Loading: An Original Mechanistic Framework Integrating Appliance Fit, Material Relaxation, and Intermittent Force Delivery in Adults with Reduced Periodontal Support

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ABSTRACT

Clear-aligner treatment begins with digitally programmed tooth displacement, yet the prescribed displacement is not itself the mechanical load experienced by periodontal tissues. Between digital planning and tissue loading lie several transformations involving aligner fit, tooth–appliance engagement, material properties, attachment configuration, time-dependent relaxation, wear interruption, changing treatment geometry, and the biomechanical consequences of reduced periodontal support. This article develops an evidence-bounded mechanistic framework for interpreting these transformations in adults whose periodontal support has been reduced by previous disease. The framework distinguishes four linked but non-equivalent states: programmed displacement, initially generated force and moment systems, temporally modified intermittent loading, and support-dependent transmission to the periodontal ligament and supporting structures. Available clinical evidence indicates that orthodontic treatment can be incorporated into carefully controlled periodontal care in selected patients, but it does not establish a universal aligner displacement, force magnitude, or loading schedule that can be considered biologically optimal for a reduced periodontium. Laboratory and computational studies further show that material composition, aligner geometry, trimline design, attachments, tooth position, and periodontal support modify force transmission, while material relaxation and evolving engagement make the delivered system time dependent. The proposed framework therefore treats realized periodontal loading as an emergent treatment state rather than a direct translation of digital prescription. Its purpose is to improve interpretation, expose unsupported assumptions, and define research requirements for clinically credible aligner biomechanics in compromised periodontal support.

Keywords: Clear aligners, Periodontal support, Orthodontic biomechanics, Force transmission, Stress relaxation, Attachment loss

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Introduction

A digital aligner setup specifies intended tooth displacement, but it does not directly specify the mechanical history experienced by the periodontal ligament, alveolar bone, or other supporting tissues. This distinction becomes especially important when periodontal support has been reduced by previous periodontitis. Contemporary periodontal classification defines periodontitis through loss of periodontal support attributable to inflammatory disease and emphasizes that disease extent, severity, complexity, and susceptibility must be interpreted within a structured diagnostic framework [1]. Staging further recognizes that two patients with periodontal attachment loss may differ substantially in remaining

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support, tooth-related complexity, functional consequences, and treatment difficulty [2]. Reduced periodontal support should therefore not be treated as a uniform biomechanical category.

For patients with advanced disease, orthodontic movement belongs within a broader interdisciplinary treatment sequence rather than operating as an isolated mechanical intervention. The European Federation of Periodontology guideline for stage IV periodontitis places orthodontic therapy among possible components of comprehensive rehabilitation once periodontal infection and inflammation have been appropriately controlled and the patient can be maintained within structured supportive care [3]. Such recommendations define clinical eligibility and responsibility, but they do not provide a numerical conversion between a programmed aligner movement and a biologically acceptable periodontal load.

Clinical evidence nevertheless supports the proposition that orthodontic treatment is not inherently incompatible with a treated, periodontally compromised dentition. Systematic syntheses have reported that orthodontic therapy can be undertaken in selected patients after periodontal management, although the underlying literature remains heterogeneous in periodontal status, treatment mechanics, outcomes, follow-up, and methodological quality [4, 5]. These findings justify continued orthodontic treatment in appropriately selected patients but do not establish a universal mechanical prescription for reduced support.

Longitudinal studies of combined periodontal and orthodontic treatment strengthen this distinction between clinical feasibility and biomechanical certainty. Regenerative periodontal therapy followed by orthodontic movement has produced favorable periodontal outcomes in carefully managed patients with severe disease [6]. In a randomized comparison of orthodontic timing after regenerative periodontal surgery, initiating orthodontic treatment substantially earlier than a conventional long waiting interval did not produce a significant disadvantage in the principal periodontal outcome [7]. Long-term observational evidence likewise indicates that periodontal stability can be maintained for many years in selected patients receiving combined regenerative, orthodontic, and supportive care [8]. These studies establish biological and clinical plausibility for tooth movement after periodontal treatment. They do not, however, reveal the exact force history experienced by individual teeth, nor do they validate any specific clear-aligner displacement as optimal for a reduced periodontium.

The central problem addressed here is therefore narrower than the question of whether orthodontic treatment can be performed in patients with previous periodontitis. It concerns the mechanical transformations occurring between a digital prescription and the load eventually transmitted to tissues with reduced support. A clear aligner must first engage the dentition and generate a force system; that system then changes with material behavior, fit, removal, reinsertion, wear, and evolving tooth position; finally, the resulting tooth-level forces and moments are transmitted through a periodontal support geometry that may differ markedly from that assumed in a periodontally intact model. Treating these stages as equivalent obscures where uncertainty enters the treatment process.

The mechanistic framework developed in this article therefore separates programmed displacement, initial appliance-generated loading, time-dependent and intermittent loading, and support-dependent periodontal transmission. This separation does not imply that each transformation can currently be measured clinically. Instead, it identifies which parts of the pathway are directly supported by experiments or clinical studies, which are principally model-derived, and which connections remain mechanistic proposals requiring validation.

Mechanical foundations of aligner force generation

Clear aligners create orthodontic forces because the manufactured appliance and the current dentition do not occupy exactly the same geometric state. Seating the appliance produces deformation and contact, and the resulting elastic response generates forces and moments at engaged tooth surfaces. A systematic biomechanical synthesis has shown that aligner-generated forces and moments vary widely according to the movement being attempted, appliance design, experimental method, and measurement configuration [9]. Consequently, the programmed displacement in the digital setup should be understood as an input to a mechanical system rather than as a direct measure of delivered orthodontic load.

Experimental measurements illustrate the importance of this distinction. In a maxillary-arch biomechanical model, identical nominal aligner activation did not produce uniform forces across teeth; tooth position within the arch materially affected measured loading [10]. The implication is not that any particular experimental force magnitude should be transferred directly to patients. Instead, the finding demonstrates that equal digital displacement can generate unequal mechanical output even before individual anatomy,

periodontal support, biological response, and intraoral wear are considered.

Computational models provide a complementary perspective because they permit detailed representation of aligner geometry, contact relationships, tooth movement, and supporting structures. Their results, however, depend on the assumptions used to build the model. Computer-aided finite-element analysis of aligners has demonstrated the sensitivity of predicted biomechanical behavior to representations of contact, geometry, materials, and boundary conditions [11]. A model can therefore clarify how a proposed system behaves under specified assumptions without proving that an identical force system occurs clinically.

The geometry of the appliance itself further modifies the transformation between prescribed movement and generated force. Experimental work examining translational movement has shown that tooth position and trimline height alter measured force and moment systems [12]. A programmed displacement consequently cannot be interpreted independently of the region in which the aligner engages the tooth and gingival margin. Apparent uniformity in the digital plan may coexist with mechanically non-uniform engagement across the dentition.

Material properties and attachment configuration introduce additional variability. Experimental and computational studies show that material composition and thickness, attachment arrangement, and attachment location can change force transmission and the balance of forces and moments generated by an aligner [13-15]. These factors should not be interpreted as independent switches that add predictable increments of force. They act through a coupled engagement system in which deformation of the aligner, local contact, tooth geometry, attachment surface, and intended movement interact.

The same point is evident when attachment orientation is considered together with movement programming. Finite-element analysis of molar distalization has shown that attachment orientation and designed vertical movement can interact to modify the simulated force system and tooth response [16]. The clinically important conclusion is therefore not that one attachment orientation has a universally superior mechanical profile. It is that appliance features can alter how a prescribed displacement becomes a force-and-moment system, and their effects depend on the movement and geometry in which they operate.

This distinction establishes the first boundary of the proposed framework. Programmed displacement describes intended geometric change; initial delivered loading describes the force and moment system created when a particular appliance engages a particular dentition. The two are related but not interchangeable. Any interpretation of periodontal loading that begins directly with the digital displacement while omitting the engagement layer risks assigning biomechanical meaning to a planning variable that has not yet been mechanically realized.

The principal appliance-level determinants identified in this section are summarized in **Table 1**. Their purpose is not to provide numerical correction factors, but to identify where a nominally identical programmed movement can diverge into different initial force systems.

Table 1. Mechanical determinants separating programmed aligner displacement from the initially delivered force system

Mechanical unit	Programmed input	Mechanism modifying delivery	Resulting biomechanical consequence	Why the programmed movement alone is insufficient	Principal interpretive limitation
Tooth position within the arch	Nominal displacement assigned to an individual tooth	Differences in local appliance deformation and neighboring contacts	Tooth-specific variation in force and moment	Equal programmed movement need not create equal loading at different teeth	Laboratory measurements depend on the tested arch and seating condition
Aligner fit and tooth–appliance contact	Intended geometric mismatch between aligner and current dentition	Distribution, loss, or concentration of contact during seating	Changes in where and how load enters the tooth	A digital setup does not specify the realized contact field	Clinical fit is difficult to represent completely in static models

Material composition	Same intended movement encoded in appliances made from different polymers	Differences in stiffness, elasticity, and deformation response	Variation in initial transmitted force	Geometric activation alone does not encode material response	Product-specific laboratory results may not generalize
Material thickness	Equivalent programmed displacement	Altered structural stiffness and deformation resistance	Change in magnitude and distribution of transmitted loading	Identical shape discrepancy can produce different mechanical output	Thickness interacts with geometry and material rather than acting independently
Trimline geometry	Same tooth movement	Different gingival extension and peripheral stiffness	Modified retention, force, and moment characteristics	The digital tooth target does not contain information about trimline behavior	Movement- and design-dependent effects prevent a universal trimline correction
Attachment presence and placement	Programmed translation, extrusion, rotation, torque, or combined movement	Modified engagement surface and local force application	Change in direction and magnitude of force/moment components	Tooth movement programming does not uniquely specify engagement mechanics	Attachment effects are strongly configuration dependent
Attachment orientation	Programmed movement with a given attachment form	Altered contact geometry between aligner and attachment	Redistribution of movement-specific force and moment	The same attachment category can act differently when reoriented	Findings from one movement cannot automatically be extended to another
Surrounding dentition and treatment geometry	Tooth-specific programmed displacement	Mechanical coupling through the continuous aligner shell	Cross-tooth dependencies and unintended components	A tooth is not mechanically isolated from the aligner system	Simplified single-tooth models may underrepresent system-level coupling

Table 1 therefore defines a necessary intermediate state between planning and periodontal loading: the initial realized appliance force system. Even this state, however, should not be considered constant after insertion. Aligners are polymeric appliances worn intermittently in a changing oral and mechanical environment, making time a second essential dimension of delivered loading.

Time-dependent and intermittent loading

The force system measured immediately after insertion represents only one moment in aligner treatment. Polymeric materials are viscoelastic, and their mechanical response changes while deformation is maintained. In laboratory testing, orthodontic aligner materials exhibited substantial stress relaxation over a 24-hour interval, with the greatest change occurring relatively early after deformation [17]. This observation provides direct evidence that an initially generated force state cannot automatically be treated as a constant load maintained throughout the recommended wear period.

Stress relaxation should nevertheless not be translated into a simple universal clinical decay curve. The laboratory condition used to measure polymer relaxation differs from an intraoral aligner repeatedly exposed to temperature variation, moisture, occlusal contact, removal, cleaning, reinsertion, and evolving tooth position. Retrieved aligners examined after intraoral use have shown surface and structural changes without demonstrating a uniform deterioration across every tested bulk mechanical property [18]. The evidence therefore supports time dependence but not a single monotonic rule in which all relevant aligner properties continuously decline at a predictable rate.

Changes at the attachment interface add another temporal mechanism. Experimental evaluation of orthodontic attachments has shown that attachment materials can undergo measurable wear under simulated service conditions [19]. Wear can plausibly alter the local engagement geometry through which an aligner generates movement-specific force components. The available evidence does not permit attachment wear to be converted into a particular percentage of force loss, however. Wear is therefore

relevant to the framework as a time-varying interface condition rather than as a validated quantitative predictor of loading decline.

Treatment geometry also changes across sequential aligners. Dynamic finite-element analysis of extraction-space closure has shown that clear-aligner force systems can evolve as the relative positions of teeth and the appliance configuration change during treatment [20]. This stage-to-stage evolution is conceptually different from stress relaxation during a single period of wear. The former reflects a changing mechanical system across treatment progression; the latter reflects a changing material and engagement state after an individual aligner has been inserted. Conflating these processes would incorrectly assign one temporal mechanism to mechanically distinct sources of variation.

Contemporary biomechanical synthesis similarly emphasizes that clear-aligner behavior emerges from interactions among material properties, geometry, attachments, tooth movement, and force transmission rather than from any single design variable [21]. A time-dependent account must therefore accommodate coupled change. For example, the force present after several hours of wear may differ from the insertion force because of material relaxation, while the force produced after reinsertion may also depend on whether tooth position, seating, or attachment engagement has changed.

Trimline evidence illustrates why universal time-independent correction factors are unlikely to be defensible. A systematic review of trimline designs found that extensions and edge configurations can alter retention and biomechanical behavior, but effects varied across experimental designs and intended movements [22]. If a trimline changes the initial engagement state, it may also alter how deformation is distributed as the aligner relaxes. Existing studies do not yet support a universal multiplier that converts a particular trimline geometry into a predictable force history.

Intermittent wear adds a further level of uncertainty that is especially relevant clinically. Aligners are removed for eating, hygiene, and other interruptions, and are subsequently reseated. Removal unloads the appliance–tooth interface, while reinsertion re-establishes contact under a potentially altered geometric state. Available evidence does not justify representing this sequence as a fixed cycle in which force falls to a known value and then returns to a known proportion of the original load. The more defensible interpretation is qualitative: clear-aligner loading is repeatedly interrupted and re-established, and the magnitude and distribution of the re-established load depend on the current state of the appliance and dentition.

This creates a second distinction within the framework. The relevant periodontal exposure is not simply the initial force measured when an aligner is first seated. It is a time-modulated loading history shaped by polymer relaxation, changing engagement, appliance removal and reinsertion, attachment condition, and progression through successive aligners. The evidence supporting each component differs in directness, and continuous intraoral loading histories remain poorly characterized. **Table 2** separates the best-supported temporal mechanisms from assumptions that remain uncertain or should not be treated as established clinical facts.

Table 2. Time-dependent biomechanical processes and unresolved assumptions in intermittent clear-aligner loading

Temporal process	What is directly supported	Mechanistic implication for delivered loading	What remains uncertain in clinical wear	Prohibited shortcut in interpretation
Polymer stress relaxation after deformation	Orthodontic aligner polymers show time-dependent stress decay under maintained laboratory deformation	Initial force may not persist unchanged through a wear interval	Exact intraoral force-time trajectory for individual appliances and patients	Treating a 24-hour laboratory relaxation curve as an in-vivo periodontal loading curve
Oral exposure of aligner material	Worn aligners can develop surface and material changes without uniform degradation of every tested bulk property	Intraoral aging can modify appliance state, but change is not necessarily simple or monotonic	Relative contribution of temperature, moisture, mastication, cleaning, and repeated removal	Assuming all relevant mechanical properties decline continuously with wear
Attachment wear	Attachment materials can lose surface volume under simulated wear	Engagement geometry may evolve during treatment	Magnitude of any resulting change in tooth-level force or moment	Converting attachment wear directly into a percentage of force loss

Sequential treatment geometry	Force and displacement patterns can change as tooth positions and aligner geometry evolve across stages	Each new stage begins from a mechanically different system	Degree to which clinical tracking reproduces modeled stage-to-stage behavior	Assuming one force system persists across the entire treatment sequence
Trimline-dependent engagement	Trimline form modifies retention and mechanical response in experimental studies	Peripheral geometry contributes to both initial seating and subsequent deformation	Interaction between trimline, repeated wear, and patient-specific seating	Applying a universal trimline correction factor
Appliance removal	Contact between aligner and dentition is temporarily discontinued	Continuous loading is interrupted	Residual biological response during unloading and effect of interruption duration	Treating prescribed wear hours as identical to uninterrupted mechanical loading
Reinsertion and refitting	Mechanical contact is re-established after removal	Loading is reapplied under the current tooth–aligner relationship	Whether the re-established load equals, exceeds, or remains below initial loading	Assuming every reinsertion completely "resets" the original force
Tracking discrepancy during a stage	Fit may progressively change if realized movement differs from programmed movement	Contact location and effective engagement can change within a wear interval	Patient-specific relationship between tracking error and actual force distribution	Equating visible fit discrepancy with a known force magnitude

The central implication is that clear-aligner treatment should be understood as an intermittent, evolving mechanical exposure rather than a sequence of constant forces. Yet even a well-characterized tooth-level force history would still not answer the clinically decisive question for a periodontally compromised patient: how that force is distributed through a tooth whose supporting structures have been reduced. That requires a separate analysis of transmission.

Transmission of aligner forces to the reduced periodontium

The transition from appliance force to periodontal tissue loading introduces a new level of analysis. Aligner shape and local contact influence how force enters a tooth before the supporting tissues are considered. Finite-element studies of extraction mechanics have demonstrated that modifying aligner geometry in the region of an extraction space changes simulated tooth displacement, stress distribution, and mechanical behavior [23]. Such findings reinforce the idea that load transmission begins with an appliance-specific contact system, but they do not yet describe the biological consequences of that load in a patient with reduced periodontal support.

Periodontal attachment loss changes the geometry through which tooth-level forces and moments are transmitted. In a patient-specific finite-element investigation that modeled different degrees of periodontal compromise, the same basic aligner-movement problem produced different periodontal-ligament stress and displacement patterns as support was reduced [24]. This is a particularly important result for the present framework because it demonstrates that the programmed displacement cannot have a support-independent mechanical meaning. As the effective supporting structures change, the biomechanical response to an otherwise comparable orthodontic input also changes.

The numerical displacement recommendations derived within such a model should not be converted into universal clinical thresholds. They depend on the anatomy, periodontal-loss representation, material assumptions, boundary conditions, and movement simulated in that particular finite-element system. Their appropriate use here is therefore mechanistic: reduced support modifies the mapping between tooth-level loading and tissue-level stress or displacement. The direction of this relationship is strongly plausible; its patient-specific magnitude remains uncertain.

Additional modeling studies show that this transmission is also sensitive to anchorage and movement configuration. Biomechanical analysis of molar intrusion using a personalized adjunct combined with clear aligners demonstrated that changes in force application and anchorage architecture altered simulated displacement and periodontal stress patterns [25]. Although the clinical illustration associated with

that work cannot establish general treatment superiority, the mechanical finding supports the broader proposition that tissue loading reflects the complete force-delivery configuration rather than the programmed tooth movement alone.

Initial tooth and posterior-segment geometry can also alter the force system developed during clear-aligner space closure. Finite-element analysis comparing different posterior inclinations found materially different displacement and stress patterns under alternative starting configurations [26]. This reinforces a clinically important boundary: two teeth assigned comparable digital movements may not experience comparable mechanical consequences if their initial geometry, neighboring contacts, anchorage, or periodontal support differs.

The reduced periodontium therefore cannot be represented as a simple scaling factor applied after an otherwise complete aligner-force calculation. Support loss changes the geometry of the load-bearing system itself. The same appliance-level force may generate a different relationship among crown displacement, root movement, periodontal-ligament deformation, center-of-resistance behavior, and alveolar support when attachment height is reduced. Conversely, a different appliance force system may sometimes produce a similar visible crown displacement while producing a different tissue-level loading state. This non-uniqueness is one reason why clinical tooth movement alone cannot reveal the complete loading history that produced it.

For adults with previously treated periodontal disease, tissue loading must also be interpreted against clinical stability rather than attachment height alone. Existing periodontal–orthodontic studies show that teeth with reduced support can be moved successfully in selected patients when inflammation is controlled and supportive care is maintained. The mechanistic framework therefore does not define reduced support as a contraindication. Instead, it identifies support geometry as a biomechanical modifier whose consequences should be interpreted alongside disease control, movement type, appliance engagement, treatment timing, adherence, and monitoring.

The relationships developed across the preceding sections are compressed in **Figure 1**.

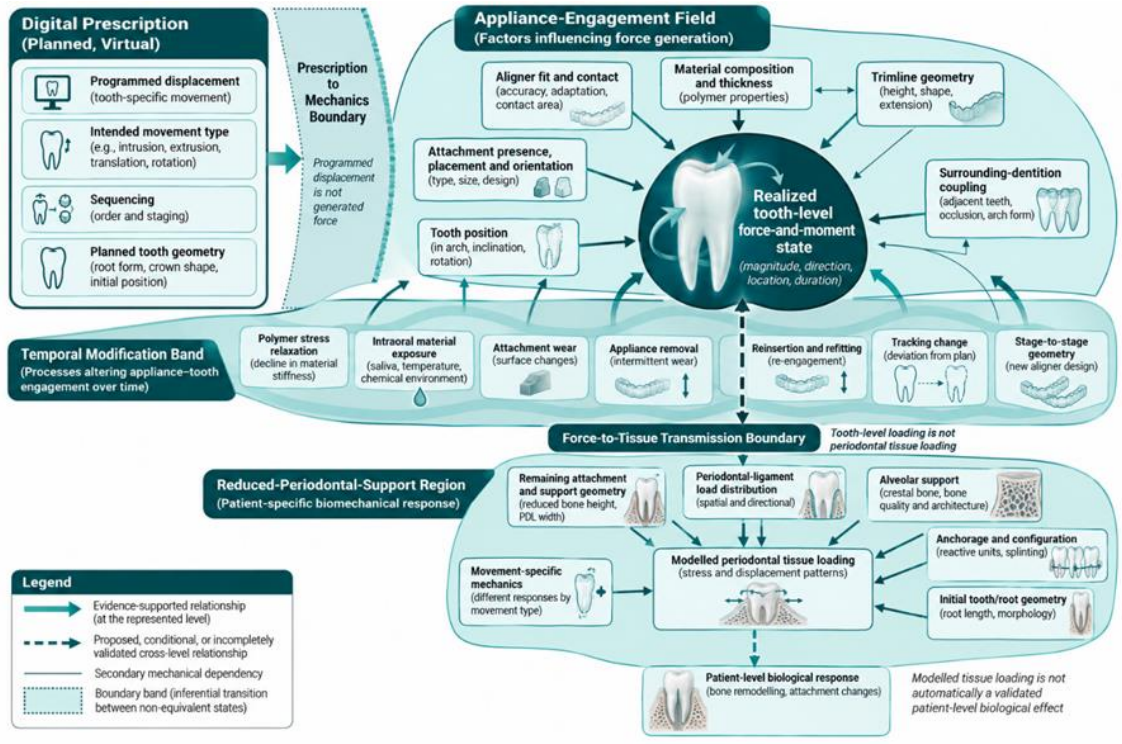


Figure 1. Layered determinants of realized periodontal loading during clear-aligner treatment in reduced support

An integrated mechanistic framework

The evidence assembled above supports a distinction between a treatment plan and the mechanical state ultimately experienced by periodontal tissues. A digital displacement first has to be realized through aligner seating, material deformation, tooth–appliance contact, trimline behavior, attachments, and the geometry of the surrounding dentition. Experimental studies demonstrate that apparently comparable programmed movements can therefore generate different force

systems [9, 10]. Those initially generated forces are themselves temporally unstable because material relaxation, evolving engagement, wear, removal, reinsertion, and stage progression can modify the mechanical state during treatment [17, 20].

A third transformation occurs when that tooth-level force system is transmitted through the supporting structures. Reduced periodontal support changes the geometry through which force and moment are converted into periodontal-ligament stress, tooth displacement, and alveolar loading [24]. The clinically realized movement is therefore the downstream product of several non-equivalent transformations rather than a direct expression of the programmed displacement. Clinical measurements showing discrepancies between digitally predicted and achieved movement further demonstrate that planned and realized movement should not be assumed to coincide [27].

The proposed mechanistic sequence is consequently: programmed displacement → appliance engagement and initial force generation → time-dependent and intermittent modification → support-dependent periodontal transmission → realized tooth movement. The individual relationships within this sequence have varying degrees of empirical support, but the complete sequence has not been prospectively measured as a single continuous process in adults with reduced periodontal support. It should therefore be interpreted as an evidence-constrained mechanistic synthesis rather than a validated predictive model.

An important consequence is that observed tooth movement cannot be used to reconstruct one unique prior periodontal loading history. Similar visible movement may arise through different combinations of contact, force decay, attachment engagement, support geometry, and biological response. Conversely, similar digital prescriptions may produce different realized loading states. This non-uniqueness defines the principal inferential boundary of the framework and motivates **Figure 2**.

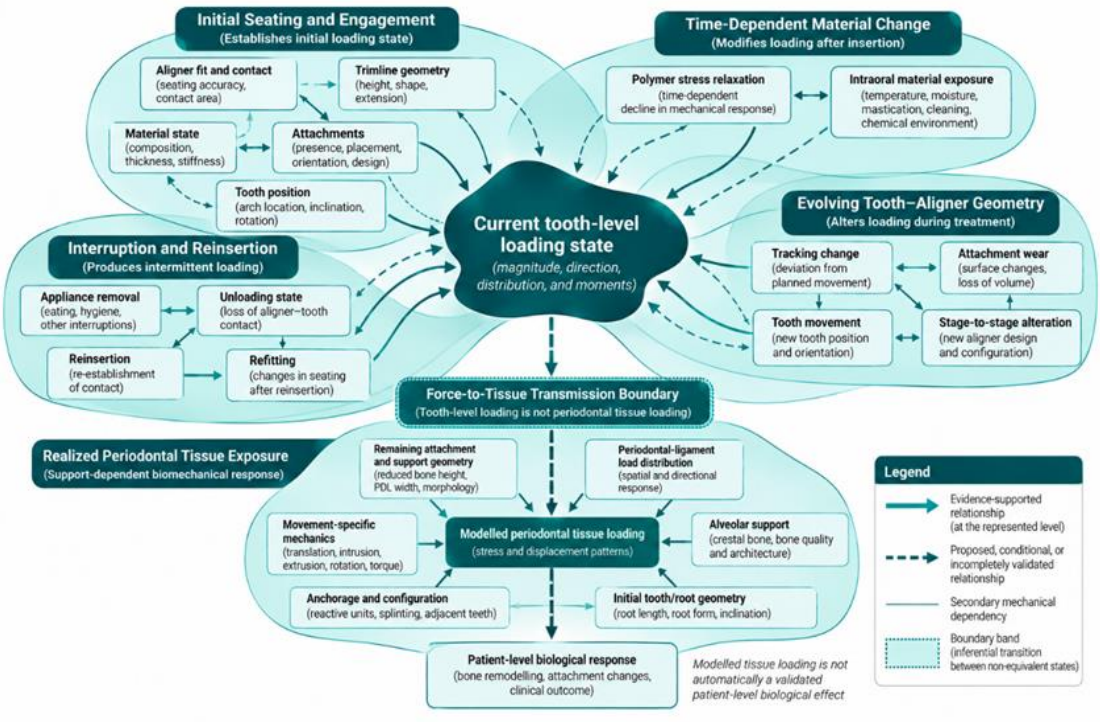


Figure 2. Intermittent loading states and constraints between aligner insertion and realized periodontal exposure

Clinical implications, model boundaries, and research needs

The framework does not imply that reduced periodontal support makes clear-aligner treatment intrinsically unsafe. In monitored orthodontic populations, clear-aligner therapy has not invariably been associated with deterioration of periodontal inflammatory measures [28]. That evidence cannot be extrapolated directly to adults with advanced attachment loss, but it provides an important counterweight to any assumption that the appliance itself necessarily causes periodontal inflammation.

Clinical decisions should therefore remain individualized. Contemporary expert consensus

recognizes both meaningful indications for clear aligners and important limits in complex biomechanics [29]. A second international consensus likewise emphasizes that aligner treatment depends on movement type, appliance design, patient factors, monitoring, and clinician judgment rather than a universally transferable mechanical prescription [30]. These consensus statements can guide clinical reasoning, but they do not substitute for direct biological validation.

The principal practical implication is consequently one of interpretation. A programmed displacement should not be read as a periodontal dose. Neither an initial laboratory force, a finite-element stress map, nor the amount of achieved tooth movement provides a complete measure of the time-varying mechanical exposure experienced by reduced periodontal tissues. In patients with previous periodontitis, these biomechanical uncertainties must remain subordinate to disease control, supportive periodontal care, movement-specific risk assessment, and reassessment of tracking and periodontal status during treatment.

Future validation should therefore connect levels that are currently studied separately. Particularly valuable studies would measure appliance fit and tooth-level force longitudinally, characterize changes after wear interruption and reinsertion, document actual movement and tracking, and relate these mechanical observations to periodontal-support geometry and biological outcomes. Patient-specific computational models may assist this work, but their clinical credibility will depend on verification against measured mechanical and biological data rather than internal model consistency alone.

The framework is consequently most useful as an interpretive discipline. It identifies where evidence is direct, where modeling supplies conditional insight, and where clinical inference exceeds what has been measured. Until these levels are connected experimentally, claims of a universally optimal aligner displacement, force magnitude, relaxation schedule, or stress threshold for the reduced periodontium remain unsupported.

Conclusion

Programmed clear-aligner displacement is not equivalent to periodontal tissue loading. Between the digital prescription and the biological structures that receive orthodontic load lie appliance fit, material behavior, attachment and trimline mechanics, time-dependent relaxation, intermittent wear, changing treatment geometry, and the altered load-bearing geometry of reduced periodontal support.

The proposed framework therefore treats realized periodontal loading as an emergent and patient-dependent mechanical state rather than a value that can be inferred directly from the digital setup. Existing evidence supports carefully controlled orthodontic treatment in selected patients with treated periodontal disease, but it does not establish a universal aligner displacement, force, or stress threshold for compromised support. Clinically defensible use of aligners in this setting requires periodontal stability, movement-specific biomechanical reasoning, monitoring, and explicit recognition of where laboratory and computational evidence ends and patient-level biological validation remains necessary.

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