



(REVIEW ARTICLE)



CLEAR ALIGNER BIOMECHANICS AND PREDICTABILITY: INHERENT MOVEMENT LIMITATIONS AND THE UNMODELLED ROLE OF MATERIAL FORCE DECAY

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ABSTRACT

Clear aligner therapy (CAT) has become a widely used alternative to fixed appliances, yet clinical predictability continues to lag behind the outcomes simulated in digital treatment-planning software. This narrative review examines two interrelated determinants of aligner biomechanical performance: inherent limitations in achieving complex tooth movements, and force decay arising from intraoral degradation of thermoplastic aligner materials. A structured search of PubMed, Scopus and Google Scholar was conducted for the period 2005 to 2026 using combinations of the terms “clear aligner,” “Invisalign,” “predictability,” “biomechanics,” “stress relaxation,” “torque,” “rotation,” and “refinement.” Movement-specific accuracy data indicate that pure bodily translation, rotation of round-shaped teeth, root torque expression, and vertical movements remain the least predictable outcomes, with reported accuracies for canine and premolar derotation as low as 36 to 55 percent, against overall movement predictability generally cited between 55 and 72 percent. Refinement is required in a substantial proportion of cases treated to completion. In parallel, in vitro studies confirm that thermoplastic aligner materials undergo rapid stress relaxation within the first hours of loading and continue to lose force-delivery capacity across the standard 7- to 14-day wear cycle, a time-dependent behaviour that current digital planning software does not incorporate into its staging algorithms. The combination of biomechanically unfavourable force systems for specific movement types and unmodelled material fatigue helps explain the persistent discrepancy between virtual treatment plans and clinically achieved outcomes. Narrowing this gap will likely require incorporation of time-dependent material behaviour into simulation software, more selective use of auxiliaries such as attachments and power ridges, shortened wear-cycle protocols, and calibrated clinician and patient expectations regarding refinement.

Keywords: Clear Aligners; Orthodontic Biomechanics; Treatment Predictability; Force Decay; Stress Relaxation; Thermoplastic Materials

1 INTRODUCTION

The concept of sequential, removable appliances for orthodontic tooth movement dates to 1945, when Kesling described the tooth-positioning appliance and proposed that a series of such devices could be used to achieve incremental movement¹. This principle remained a laboratory curiosity until the introduction of computer-aided design and manufacturing in the late 1990s, which allowed the fabrication of full series of thermoformed aligners from a single

digital treatment plan. Clear aligner therapy (CAT) has since progressed through successive generations of material, attachment and staging refinements², and adoption has expanded from mild crowding cases to a broad range of malocclusions, including extraction and interdisciplinary treatment.

Despite this growth, clinicians and patients continue to encounter a gap between the tooth positions simulated in digital treatment-planning software and the positions clinically achieved at the end of a given aligner stage. The first systematic review of Invisalign treatment effects, published in 2005, identified only two eligible studies and could draw no firm conclusions regarding efficacy³, underscoring how recent the evidence base for CAT predictability still is relative to that for fixed appliances. Subsequent scoping and systematic reviews have consistently reported that predictability varies markedly by movement type, and that certain categories of movement — bodily translation, root torque, rotation of round-shaped teeth, and vertical movement — remain disproportionately difficult to achieve as planned^{4,5}.

Two distinct but interacting explanations have been proposed for this shortfall. The first is biomechanical: the aligner delivers force through a pushing, shape-molding mechanism rather than the bracket-and-wire pulling mechanism of fixed appliances, which inherently limits the range of movements that can be controlled without auxiliaries. The second is material-related: thermoplastic aligner materials are viscoelastic and undergo stress relaxation under sustained deformation, so the force initially built into the appliance at the time of thermoforming is not the force delivered throughout the prescribed wear cycle. Digital treatment-planning platforms model the geometric endpoint of each staged movement but do not, at present, incorporate the time-dependent mechanical behaviour of the material delivering that movement. This review examines the current evidence for both limitations and considers their combined effect on clinical predictability.

2 MATERIALS AND METHODS

This is a narrative literature review rather than a registered systematic review or primary clinical study; no ethical approval or informed consent was required, as no patient data, human tissue or animal subjects were used. A structured, non-exhaustive search of PubMed/MEDLINE, Scopus and Google Scholar was performed for articles published between January 2005 and September 2026. Search terms were combined using Boolean operators and included: “clear aligner,” “Invisalign,” “aligner therapy,” “tooth movement predictability,” “orthodontic biomechanics,” “rotation,” “torque,” “intrusion,” “extrusion,” “refinement,” “thermoplastic,” “stress relaxation,” and “force decay.” Reference lists of retrieved systematic reviews, scoping reviews and meta-analyses were hand-searched for additional primary studies.

Eligible sources included systematic reviews, meta-analyses, prospective and retrospective clinical accuracy studies using three-dimensional digital-model superimposition, in vitro mechanical and stress-relaxation studies of aligner materials, and finite-element analyses of aligner force systems. Case reports, conference abstracts, non-peer-reviewed sources, and articles not available in English were excluded. Because of substantial heterogeneity in aligner brand, attachment protocol, wear-cycle duration, and outcome-measurement methodology across the included literature, no meta-analysis was attempted; findings are synthesised narratively and organised by movement type and by material behaviour, consistent with the format of prior scoping reviews in this field^{4,5}.

3 RESULTS AND DISCUSSION

3.1 Inherent Movement Limitations

Across clinical accuracy studies using pre-treatment, planned, and post-treatment digital model superimposition, overall dental movement predictability with clear aligners is commonly reported in the range of 55 to 72 percent, with substantial variation by tooth type and movement category⁶. This headline figure conceals a consistent pattern in the underlying data: some movements are executed with reasonable fidelity, while others fall well short of the virtual plan even after accounting for staging and overcorrection built into the software.

Rotational correction of round-shaped teeth is among the most extensively documented limitations. Canines and premolars, whose roughly conical cross-section provides limited surface area for the aligner shell to engage, show markedly lower rotational accuracy than incisors or molars. A prospective study of canine derotation reported an average accuracy of only 36 percent, rising modestly to 43 percent when interproximal reduction was performed concurrently⁹. A meta-analysis of software-predicted versus clinically achieved rotation similarly concluded that rotational movement carries the highest level of inaccuracy of any movement category, particularly for round teeth⁸. More recent three-dimensional superimposition data have reported improved overall rotational accuracies of 75 to 79 percent with attachment protocols and interproximal reduction⁷, indicating that auxiliaries and refined staging narrow but do not eliminate this gap.

Pure bodily translation and root torque present a related but distinct challenge. Because the aligner engages the clinical crown rather than the root, and because plastic shells generate a force couple that is difficult to control precisely without a rigid engagement point, torque expression and translational movements that require sustained root-level control are systematically under-expressed relative to the digital plan. Even with attachments, one clinical study of incisor torque, premolar derotation and molar distalisation reported torque accuracies in the range of 42 to 47 percent¹², and biomechanical analyses of aligner force systems have confirmed that the moment-to-force ratios generated by unmodified aligner shells are frequently unfavourable for the pure root movement intended¹¹. Auxiliaries such as power ridges and optimised attachments are designed specifically to shift the aligner's centre of force application closer to the root and improve this ratio, but their benefit is partial rather than complete, and their own retention and fit are themselves subject to the material behaviour discussed in Section 3.2.

Severe rotations, transverse expansion, overbite correction and vertical movements — extrusion and, in particular, intrusion — are consistently identified in scoping reviews as the least predictable movement categories overall, with intrusion singled out repeatedly as the single most unreliable objective in clear aligner treatment planning^{4,5}. This is consistent with the underlying biomechanical constraint that extrusive and intrusive forces are the most difficult of all tooth movements to generate with a passive, tooth-borne appliance lacking a fixed anchorage point, and it explains why aligner protocols for these movements rely heavily on auxiliaries, elastics or temporary anchorage devices rather than the aligner shell alone.

The cumulative clinical consequence of these movement-specific limitations is a substantial rate of treatment refinement. Retrospective studies of patients requiring additional aligner sets after their initial series report refinement in a large proportion of cases, and a meaningful minority of patients ultimately convert from aligner therapy to fixed appliances to complete correction^{17,18}. Refinement is not, in itself, evidence of treatment failure — it is, in effect, a built-in second staging cycle that compensates for the accumulated inaccuracy of the first — but its frequency indicates that the initial digital setup should be understood by clinicians and patients alike as a starting hypothesis rather than a guaranteed outcome, particularly for cases involving rotation of round teeth, torque control, or vertical movement.

3.2 Material Fatigue and Force Decay

Clear aligners are manufactured from thermoplastic polymers — principally polyethylene terephthalate glycol (PETG), thermoplastic polyurethane (TPU), and multilayer or polycarbonate-blend variants — chosen for a combination of transparency, biocompatibility and elastic recovery¹³. These materials are, however, viscoelastic rather than purely elastic: when deformed to fit a malaligned dental arch and held at that deformation, the internal stress required to maintain the shape decreases progressively over time even though the geometric deformation itself does not change. This phenomenon, stress relaxation, is distinct from simple wear and is an intrinsic property of the polymer network.

In vitro three-point bending studies quantifying this behaviour over clinically relevant wear periods report that the majority of force loss occurs within the first hours of loading, after which the rate of decay slows but does not plateau to zero. In a 24-hour analysis of four aligner materials, all four exhibited measurable stress relaxation, with meaningful differences between products¹⁴. A subsequent 14-day in vitro study of five materials extended this picture across a full clinical wear cycle: two of the five materials retained approximately 37 to 39 percent of their initial stress by day 14 or 15, while the remaining materials retained under 5 percent, despite all materials showing the same characteristic pattern of rapid early decay followed by a slower approach to a low plateau¹⁵. This magnitude and rate of decay varies by polymer chemistry, layer construction (single- versus multilayer sheet), and material thickness, meaning that force delivery at the end of a 7- to 14-day wear interval may differ substantially, both in absolute terms and as a fraction of the initial value, from the force assumed at the moment of virtual treatment planning.

This effect is compounded by physical changes to the aligner shell itself during intraoral use. A prospective clinical study measuring aligner thickness before and after ten days of intraoral wear found measurable thinning of the shell material following thermoforming and clinical service¹⁶, which independently reduces the stiffness — and therefore the force-delivery capacity — of the appliance as the wear cycle progresses, on top of the stress-relaxation effect described above. Mastication, temperature cycling between ambient and intraoral conditions, and repeated removal and reinsertion further subject the material to cyclical mechanical loading that is not replicated in static bench testing, and current evidence suggests it may contribute additional, less predictable stiffening or force variation beyond stress relaxation alone.

The clinically material point is that digital treatment-planning software — including the ClinCheck-type platforms used to generate the staged virtual setup — models each aligner stage as a fixed geometric target achieved by a notionally constant force, without incorporating the time-dependent decline in that force across the prescribed wear interval. In practice, this means the force actually available to move a given tooth is highest immediately after aligner insertion and lowest toward the end of the 7- to 14-day cycle, precisely when — for movements requiring sustained root control, such as torque correction reliant on a power ridge engaging the gingival third of the aligner — consistent force delivery

matters most. Because staging algorithms distribute the total prescribed movement evenly across a fixed number of aligner steps without reference to this decay curve, the discrepancy between planned and delivered force compounds across a full course of treatment consisting of twenty or more stages, contributing independently to the gap between ClinCheck simulation and clinical expression described in Section 3.1.

Some manufacturers and clinicians have responded empirically by shortening the aligner-change interval from the traditional 14 days to 7 days, on the reasoning that force delivery in the second week of wear falls below a clinically useful threshold for many materials. This strategy is a reasonable clinical workaround but does not resolve the underlying planning-software limitation: it changes the frequency at which a decaying force curve is reset, rather than incorporating that curve into the prediction of tooth displacement per stage. A more fundamental solution would require aligner-planning algorithms to incorporate material-specific stress-relaxation data — potentially informed by time-temperature superposition modelling of the kind now emerging in materials-science literature — so that staged tooth movement per aligner reflects the force realistically available across the full wear cycle rather than the initial, unrelaxed force alone.

4 CONCLUSION

Clear aligner therapy remains constrained by two compounding sources of inaccuracy. First, its passive, tooth-borne force delivery mechanism is inherently less capable of controlling pure bodily translation, root torque, severe rotation of round-shaped teeth, and vertical movement than fixed appliances, even with contemporary attachment and power-ridge designs. Second, the thermoplastic materials from which aligners are manufactured undergo measurable, material-dependent stress relaxation across the standard 7- to 14-day wear cycle, a time-dependent force decay that current digital treatment-planning software does not model. Together, these factors help explain why overall movement predictability remains in the range of roughly 55 to 72 percent and why refinement is a common rather than exceptional feature of aligner treatment. Improving predictability will likely depend on integrating material-specific force-decay data into staging algorithms, continued refinement of attachment and power-ridge design for torque- and rotation-dependent movements, judicious use of shortened wear-cycle protocols where indicated, and transparent communication with patients that a degree of refinement should be anticipated as part of, rather than a deviation from, a well-managed course of clear aligner treatment. Prospective studies directly linking in vitro force-decay profiles of specific materials to their clinically achieved accuracy for matched movement types represent a priority area for future research.

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