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Review

Beyond Nominal Thickness: The Influence of Aligner Thickness on Clear Aligner Biomechanics—A Critical Narrative Review

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Abstract

Foil thickness is one of the most frequently used design parameters to modulate the load transmitted by clear aligners, yet its relationship with the achieved tooth movement remains unclear. This critical narrative review, based on a structured search in PubMed and Scopus (last search: 3 October 2026), synthesizes the experimental, computational, and clinical evidence regarding the effect of thickness on the initial mechanical response, manufacturing-related dimensional changes, and transverse, sagittal, and vertical movements. With comparable materials and geometries, an increased thickness raises initial forces, moments, and calculated periodontal stresses, although this effect depends on the polymer, layer structure, activation, gingival margin, and auxiliaries. Thermoforming preserves approximately 35% to 90% of the original thickness depending on the region, technique, and model height; since local bending stiffness scales with the cube of thickness under classical plate theory, these losses may have disproportionate mechanical consequences. Directly printed aligners show the opposite deviation. Comparative clinical evidence is currently limited to a single small randomized trial. A universal or movement-specific optimal thickness cannot be recommended: thickness should be treated as a measured regional magnitude rather than a nominal value.

Keywords: clear aligners; thickness; biomechanics; thermoforming; 3D printing; finite element analysis; bending stiffness; tooth movement

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1. Introduction

Clear aligners transmit loads to the teeth through the deformation of a continuous polymeric shell. Unlike fixed appliances, where force is applied at discrete points through the bracket, the load generated by an aligner results from multiple simultaneous contacts whose distribution depends on the crown geometry, material properties, and the discrepancy between the appliance shape and the actual tooth position [1,2]. Within this system, foil thickness is the design variable that clinicians and manufacturers can most easily modify. Commercial foils typically range from 0.5 to 1.0 mm [3–5], and protocols of increasing thickness within the same stage have been proposed to grade the load, such as the 0.4–0.5–0.75 mm sequence [6,7].

Research on this variable has developed across three rarely connected planes. The first group of studies measures initial forces and moments in flat foils or thermoformed appliances on instrumented models [3,4,8]. The second group quantifies the material lost during thermoforming and how this loss is distributed across the arch [9–11]. The third

group simulates, using finite element analysis, the initial displacement and periodontal stresses produced by different thicknesses [12–14]. This fragmentation complicates translating an increase in stiffness measured in the laboratory into an improvement in precision, root control, or treatment safety, especially when studies use different outcomes: absolute force, moment, moment-to-force ratio, initial displacement, periodontal ligament stress, or achieved clinical movement [15].

Furthermore, an explicit mechanical framework is lacking. The bending stiffness of a foil is not proportional to its thickness, but to its cube; thus, differences in a few tenths of a millimeter—in the order of those introduced by manufacturing—can substantially alter the transmitted load. This relationship has barely been used to interpret the orthodontic literature, even though it explains much of its apparent heterogeneity.

The objective of this review is to critically integrate the evidence regarding the relationship between thickness and the biomechanical behavior of aligners, with four purposes: to propose an interpretative mechanical framework; to identify the manufacturing factors that determine the actual thickness in both thermoformed and directly printed appliances; to assess how the effect of thickness varies according to transverse, sagittal, or vertical movements; and to distinguish experimental and computational findings from clinical outcomes.

2. Materials and Methods

2.1. Study Design

A critical narrative review, rather than a systematic one, was conducted, and the manuscript was checked against the six items of the SANRA scale (Scale for the Assessment of Narrative Review Articles) [16]: justification, aims, search strategy, referencing, scientific reasoning, and appropriate presentation of data. SANRA is an instrument for appraising the quality of narrative reviews, not a reporting guideline; it was used here as a checklist to make sure that each of its six items was explicitly addressed. The protocol was not registered, as the design does not intend to provide an aggregated quantitative estimate.

2.2. Search Processing

Studies were identified through two electronic databases, PubMed/MEDLINE and Scopus. The last search was run on 3 October 2026.

The following search strategy was carried out using the appropriate descriptors, according to the subject, linked by Boolean operators:

- Clear aligner AND orthodontics;
- Clear aligner AND thermoplastic appliance AND orthodontics;
- Clear aligner AND thermoplastic material AND orthodontics;
- Clear aligner AND thermoplastic material.

The strings were deliberately broad. Aligner thickness is seldom indexed as a keyword or MeSH term and is often reported only in the methods or as a secondary variable, so adding thickness-specific terms at the search stage risked missing eligible studies. Thickness-related eligibility was therefore assessed during screening rather than through the search strings.

The search strings were entered as follows, using the default search field of each database. In PubMed, terms were searched in All Fields with automatic term mapping, so that "orthodontics" was also searched through its MeSH heading:

- #1: clear aligner AND orthodontics;
- #2: clear aligner AND thermoplastic appliance AND orthodontics;
- #3: clear aligner AND thermoplastic material AND orthodontics;
- #4: clear aligner AND thermoplastic material.

In Scopus, the same terms were searched in the article title, abstract, and keyword fields:

- #1: TITLE-ABS-KEY (clear aligner AND orthodontics);
- #2: TITLE-ABS-KEY (clear aligner AND thermoplastic appliance AND orthodontics);
- #3: TITLE-ABS-KEY (clear aligner AND thermoplastic material AND orthodontics);
- #4: TITLE-ABS-KEY (clear aligner AND thermoplastic material).

We recorded the total number of results in a table, organized by database and search strategy (Table 1).

Table 1. Search results by database and search strategy used. Values are raw hits before removal of duplicates; searches were run on 3 October 2026.

	PubMed	Scopus
Clear aligner AND orthodontics	155	113
Clear aligner AND thermoplastic appliance AND orthodontics	134	112
Clear aligner AND thermoplastic material AND orthodontics	90	77
Clear aligner AND thermoplastic material	65	54

2.3. Selection Criteria

In vitro, computational, morphometric, and clinical studies were included if they met at least one of the following conditions: comparing two or more nominal or design thicknesses; measuring the actual thickness of aligners or foils after manufacturing or use; or relating thickness to forces, moments, displacements, periodontal stresses, or clinical outcomes. Articles published in English or Spanish were eligible for inclusion. Studies published in other languages were also considered when their full texts could be assessed using machine translation. Two included studies, published in Korean [17] and Chinese [18], were assessed in full text with the assistance of machine translation. Studies on retainers, those not treating thickness as a variable, conference abstracts, and papers published in journals removed from Scopus for non-compliance with editorial standards were excluded. The flow chart (Figure 1), adapted from the PRISMA 2020 flow diagram [19] to the narrative design of this review, summarizes the selection process.

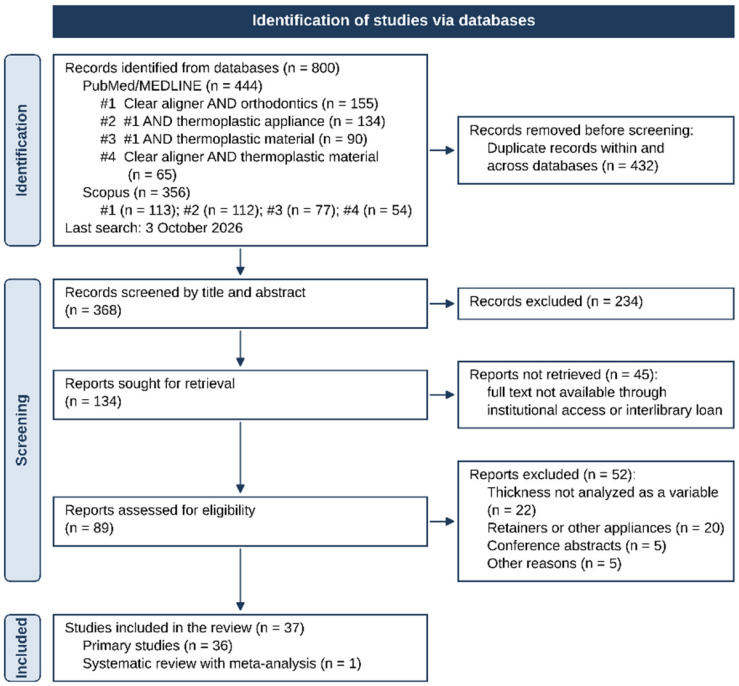

Figure 1. Flow chart of study selection, adapted from the PRISMA 2020 flow diagram [19].

After removal of duplicates, 368 records were screened by title and abstract. Of the 134 reports sought for retrieval, 45 could not be obtained because the full text was not available through institutional access or interlibrary loan. Of the 89 reports assessed in full, 52 were excluded for the following reasons: thickness not analyzed as a variable ($n = 22$); retainers or other appliances ($n = 20$); conference abstracts ($n = 5$); and other reasons ($n = 5$). These reasons are also given in Figure 1.

2.4. Selection, Extraction, and Classification of Evidence

Two reviewers (D.C.A. and D.M.L.) independently screened all titles, abstracts, and full texts; disagreements were resolved by discussion and, when agreement was not reached, by a third reviewer (A.J.L.J.). For each study, the study design, material, nominal or design thicknesses, measured thickness (when reported), evaluated movement, measurement method, and primary outcome were recorded. The evidence was classified by design (clinical, in vitro experimental, computational, or morphometric) and interpreted according to that specific level of evidence. A formal risk of bias tool was not applied because there is no common validated instrument applicable to mechanical tests, finite element models, and micro-CT studies simultaneously; instead, a structured qualitative appraisal adapted to each design was carried out. For the randomized trial, the five domains of the RoB 2 tool were considered [20]. For in vitro mechanical and morphometric studies, the criteria were drawn from the QUIN tool [21]: sample size and its justification, standardization of specimens and activation, control of temperature and humidity, calibration and reliability of the measuring system, and the number of independent specimens. For finite element studies, the material models of the aligner and periodontal ligament, contact and boundary conditions, mesh convergence, and experimental validation were considered, following published recommendations for reporting finite element studies in biomechanics [22]. The main limitation of each study is given in Table 2, and these limitations were taken into account when grading the strength of each conclusion (Table 3) and in the Discussion. Ultimately, 36 primary studies and one systematic review with meta-analysis were included (Table 2).

Table 2. Main characteristics of the included studies, by domain.

Study	Design	Material and Thicknesses	Movement/ Variable	Main Finding Regarding Thickness	Main Methodological Limitation
Mechanical response					
Gao and Wichelhaus 2017 [1]	In vitro, 6-component sensor	PET-G 0.5/0.625/ 0.75 mm; 3 margins	Palatal tipping and intrusion	Significant difference only between 0.5 and 0.75 mm; gingival margin influence is equal or greater	Single incisor; initial loading only
Elshazly et al. 2024a [2]	In vitro, pressure films	Monolayer and multilayer; 0.50–0.89 mm	Normal force on incisor	Higher force with 0.75 than 0.50 mm; multi-layer < monolayer	Pressure films: integrated normal load, no force–moment vector; static
Kwon et al. 2008 [3]	In vitro, 3-point bending	3 materials; 0.508/0.762/ 1.016 mm	Force and recovery energy	Useful deflection 0.2–0.5 mm; thinner foil returns more energy in that range	Flat specimens; no aligner–tooth contact

Table 2. *Cont.*

Study	Design	Material and Thicknesses	Movement/ Variable	Main Finding Regarding Thickness	Main Methodological Limitation
Hahn et al. 2009 [4]	In vitro, thermoformed appliance	Erkodur 0.8/1.0; Biolon 0.75/ 1.0 mm	Central incisor tipping	Fx 1.62–5.35 N; higher force with thicker foils	Single incisor; one activation; initial loading only
Elkholy et al. 2016 [6]	In vitro, 3D sensor	PET-G 0.3–0.75 mm	Labiopalatal translation of tooth 11 ± 0.25 mm	−35% (0.4 mm) and −71% (0.3 mm) compared to 0.5 mm; 0.3 mm unstable	Single incisor (tooth 11); initial loading only; novel 0.3–0.4 mm foils
Elkholy et al. 2017 [7]	In vitro, 3D sensor	PET-G 0.3–0.75 mm	Derotation ±10°	Moments of 73.6, 41.1, and 17.8 N·mm (0.5/0.4/0.3 mm); nonlinear return	Single incisor; initial loading only
Kohda et al. 2013 [8]	In vitro, thermoformed appliance	3 materials (Duran, Erkodur, Hardcast); 0.4–0.5 vs. 0.75–0.8 mm	Bodily movement; 0.5/1.0 mm activation	Higher force with thicker foils; 1.0 mm activation yields less force than 0.5 mm	Initial force only; two activations
Liu and Chen 2015 [12]	Finite elements	0.5–1.25 mm	Periodontal ligament stress	Stress tripled between 0.75 and 1.25 mm	Computational; no clinical validation; model-dependent values
Seo et al. 2021 [13]	Finite elements (viscoelastic PDL)	0.5/0.75 mm	Lingual inclination and rotation	+6% principal stress with 0.75 mm; similar center of rotation	Computational; no clinical validation
Iliadi et al. 2019 [15]	Systematic review and meta-analysis	13 studies; 2 meta-analyzed	Moment-to-force ratio	No M/F difference between 0.5, 0.625, and 0.75 mm in palatal tipping	Only two studies meta-analyzed; in vitro primary data
Ryu et al. 2018 [23]	In vitro, multiscale	4 materials; 0.5–1.0 mm	Properties before and after thermoforming	Flexural modulus changes in different directions depending on material and thickness	Material properties only; no tooth movement
Lombardo et al. 2017 [24]	In vitro, 24 h	2 monolayers, 2 bilayers	Stress relaxation	>50% loss in the first few hours; plateau from ~8 h	Flat specimens; materials compared, thickness not varied; 3 tests per material
Min et al. 2010 [17]	In vitro, bending	4 products; various thicknesses	Force after repeated loading	Thickness × deflection interaction; −10% to −17% force after 5 cycles	Flat specimens; five loading cycles; Korean full text

Table 2. *Cont.*

Study	Design	Material and Thicknesses	Movement/ Variable	Main Finding Regarding Thickness	Main Methodological Limitation
Elshazly et al. 2024b [25]	Finite elements	0.3–0.6 mm; 4 margins	Vestibular translation 0.2 mm	Force 1.0–2.2 N, higher with thickness and extended straight margin; tipping in all designs	Computational; single-tooth translation; no clinical validation
Lyu et al. 2023 [26]	Finite elements + in vitro	0.50/0.75 mm; 6 margins	Space closure	Higher stress with 0.75 mm; no clear relationship with movement control	Stress, not achieved movement, as outcome
Manufacturing and actual thickness					
Bucci et al. 2019 [9]	Prospective clinical ($n = 18$)	PET-G 0.75 mm, vacuum	Occlusal thickness after 10 days of use	0.38–0.69 mm after thermoforming; stable after 10 days	One material and thickness; occlusal points only; 10 days
Lombardo et al. 2020 [10]	Micro-CT	6 systems, same nominal thickness	Gap and thickness	Significant differences among brands	Single model; same sample as Palone et al.
Palone et al. 2021 [11]	Micro-CT	6 systems (same group as Lombardo)	Gap and thickness by region	Anterior teeth and gingival/coronal centers are thinner	Same sample as [10]; selected slices
Ghoraba et al. 2024 [27]	In vitro + micro-CT	Zendura FLX (multilayer); 15–30 mm models	Thickness and normal force	Force 88.9 → 45.7 N with taller models; 50–85% thickness preserved	One material; pressure films for force
Tran and Pham 2026a [28]	In vitro, caliper ($n = 10$)	Zendura FLX (multilayer) 760 µm	Thickness by tooth and surface	404 µm (anterior) to 482 µm (molar); vestibular < palatal	Caliper point measurements; one material
Tran and Pham 2026b [29]	In vitro, caliper ($n = 40$)	Zendura FLX (multilayer) 760 µm; 2–8 mm bases	Thickness according to base height	446 → 268 µm from 2 to 8 mm	Caliper point measurements; one material
Mantovani et al. 2021 [30]	Micro-CT ($n = 20$)	Invisalign	Thickness homogeneity	0.566–0.644 mm; molar gingivolingual edge 0.068 mm thinner	One commercial system; selected sections
Cupolillo et al. 2026 [31]	Micro-CT ($n = 30$)	PET-G; 3 thermoforming techniques	Thickness by region	467/429/380 µm (pressure/digital vacuum/conventional vacuum)	One material; in-office thermoforming only
Krishnakumaran et al. 2025 [32]	Nano-CT ($n = 16$)	PET-G and TPU 0.75 mm; 2 machines	Gap and thickness	Machine effect limited to molar region; increasing thickness towards anterior	Pilot study; small sample ($n = 16$)
Allaf et al. 2026 [33]	In vitro, caliper	10 brands; 1 or 2 models	Thickness by region	Dual-model fabrication: similar or slightly higher thickness	Caliper point measurements

Table 2. *Cont.*

Study	Design	Material and Thicknesses	Movement/ Variable	Main Finding Regarding Thickness	Main Methodological Limitation
Direct 3D printing					
Kim and Park 2025 [34]	Micro-CT ($n = 30$)	Thermoformed vs. printed	Fit and thickness in embrasures	Thermoformed 36.5–88.5% of the foil; printed 197–470% of the design	Embrasures only; single model
Edelmann et al. 2020 [35]	In vitro, optical scanning	SLA resins; 0.5/0.75/1.0 mm design	Actual vs. design thickness	+0.25–0.27 mm over the design	Design–print deviation only; no mechanical testing
McCarty et al. 2020 [36]	In vitro, optical scanning	SLA resin; 3 orientations; post-curing	Dimensional accuracy	Minimal overall effect; localized deviations	One resin and design; no mechanical testing
Specific movements					
Gómez et al. 2026 [5]	In vitro, randomized ($n = 60$)	PET-G 0.76/1.02 mm; 3 margins	Transverse forces	Maximum with 1.02 mm and extended straight margin; anteroposterior decrease	Transverse forces only; no tooth movement
Li et al. 2024 [14]	Finite elements	0.5/0.75 mm; 7 patterns	Expansion	Greater displacement and stress with 0.75 mm; tipping predominance	Computational; initial displacement only
Cheng et al. 2026 [18]	Finite elements	4 thicknesses; 4 margins	Molar distalization	Greater displacement and stress with increased thickness; margin determines anchorage	Computational; Chinese full text
Cheng et al. 2022 [37]	Finite elements	0.5/0.75 mm; power ridge	Retraction with torque	Power ridge of 0.7 mm (0.5) vs. 0.25 mm (0.75) for incisor translation	Computational; single extraction model
Alhasyimi et al. 2024 [38]	Finite elements	0.75–1.15 mm; 3 attachments	Anterior retraction	Higher stress with increased thickness; 0.75–0.85 mm proposed on stress criteria only	Computational; optimum defined by stress
Jin et al. 2024 [39]	Finite elements + experimental	Localized posterior reinforcement	Retraction with extractions	Less posterior mesial tipping; reinforcement also alters geometry	Reinforcement changes geometry as well as thickness
Kang et al. 2025 [40]	Finite elements (preprint)	Gradient gingival thickness	Incisor torque in retraction	Less undesired lingual inclination in some configurations	Preprint, not peer-reviewed; computational
Tosun and Eglenen 2025 [41]	Finite elements	0.75/0.95/1.15 mm; 3 attachments	Posterior intrusion 0.2 mm	Maximum 0.115 mm with 1.15 mm and beveled attachment	Computational; thickness and attachment effects not separable

Table 2. *Cont.*

Study	Design	Material and Thicknesses	Movement/ Variable	Main Finding Regarding Thickness	Main Methodological Limitation
Clinical evidence					
Cengiz and Göymen 2025 [42]	Randomized trial ($n = 28$)	0.5/0.75 mm, in-office thermoformed	Mild crowding, Class I	More expansion with 0.75 mm; more pain and lower satisfaction	$n = 28$; retrospective registration; mild crowding only; arch dimensions, not planned-vs-achieved accuracy; RoB 2: "some concerns"

Table 3. Integrated reading of the evidence by domain.

Domain	Representative Studies	Convergent Finding	Limit of Inference
Mechanical response	Hahn (2009) [4]; Kohda (2013) [8]; Elkholy (2016) [6] (2017) [7]; Gao (2017) [1]; Iliadi (2019) [15]; Elshazly (2024) [2]	For the same material, greater thickness increases initial force and moment	Does not consistently modify the moment-to-force ratio nor demonstrate better control
Behavior over time	Kwon (2008) [3]; Min (2010) [17]; Lombardo (2017) [24]; Ryu (2018) [23]	Rapid stress relaxation; thermoforming alters the modulus	Initial force is poorly representative of the load during use
Manufacturing and actual thickness	Bucci (2019) [9]; Lombardo (2020) [10]; Palone (2021) [11]; Cupolillo (2026) [31]; Tran (2026) [28,29]; Krishnakumaran (2025) [32]	Thermoforming reduces and redistributes thickness	Regional pattern depends on technique, model height, and material
Direct 3D printing	Edelmann (2020) [35]; McCarty (2020) [36]; Kim (2025) [34]	Actual thickness exceeds design thickness	Few studies and highly diverse resins
Expansion	Li (2024) [14]; Gómez (2026) [5]; Cengiz (2025) [42]	Greater force and displacement with increased stiffness	Tipping predominance; root control not demonstrated
Torque, retraction, and distalization	Cheng (2026) [18]; Lyu (2023) [26]; Alhasyimi (2024) [38]; Jin (2024) [39]; Kang (2025) [40]	Thickness interacts with compensations and anchorage	Almost exclusively finite elements; confounding variables
Intrusion and extrusion	Gao (2017) [1]; Tosun (2025) [41]	Greater calculated intrusion with increased stiffness and attachments	No data for intentional extrusion
Clinical efficacy	Cengiz (2025) [42]; Bucci (2019) [9]	More expansion with 0.75 mm, accompanied by more pain	A single small trial, retrospectively registered

3. Mechanical Foundation: Why Nominal Thickness Is Not Enough

In a thin plate subjected to bending, the stiffness per unit width is $D = E \cdot t^3/[12(1 - \nu^2)]$, where E is the elastic modulus, t is the thickness, and ν is Poisson's ratio. For the same material, a 0.75 mm foil that retains 0.60 mm in a given region after thermoforming will have approximately 51% of the original foil's bending stiffness in that area under the flat-plate assumption; if it retains 0.45 mm, it will have about 22% (Figure 2). An aligner is not a flat

plate: its curvature causes part of the load to be resisted by tension and compression in the plane of the foil, a membrane behavior where stiffness scales approximately linearly with thickness. The actual response lies between these two extremes and depends on local geometry, but in both situations, the loss of thickness reduces stiffness, and in areas dominated by bending, it does so disproportionately.

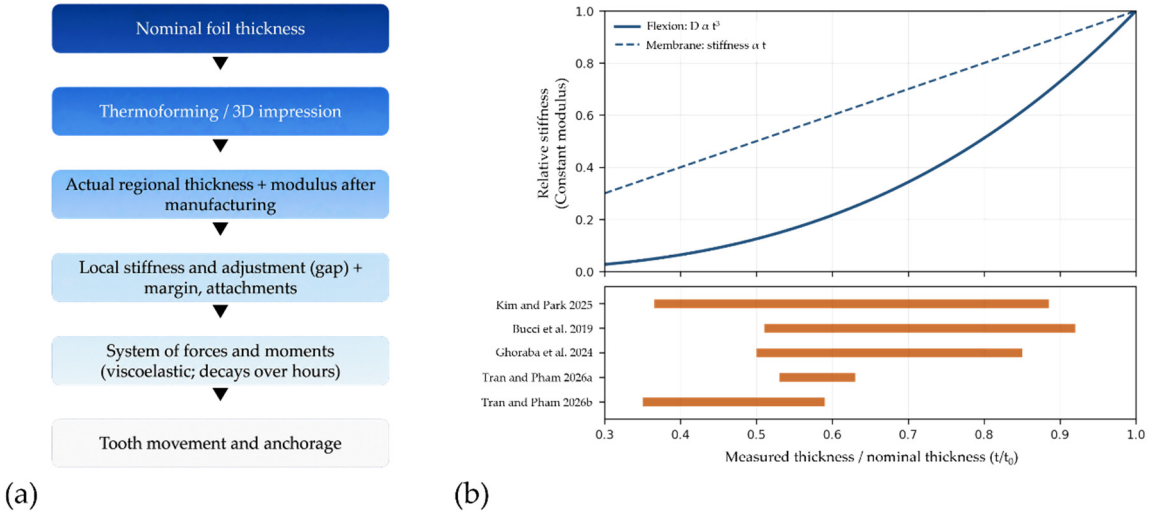

Figure 2. (**a**) Causal chain between the nominal foil thickness and tooth movement. Each link introduces variables not captured by the nominal thickness. (**b**) Top: relative stiffness as a function of the preserved thickness fraction, assuming a constant elastic modulus; the bending stiffness of a plate ($D \propto t^3$, solid line) and the membrane stiffness ($\propto t$, dashed line) bound the behavior of a curved shell. Bottom: ranges of measured thickness relative to the nominal value reported in studies with a known starting thickness (0.75–0.76 mm foils, except for Kim and Park, who express the ratio relative to the original foil of each group) [9,27–29,34]. Panel (**b**) is a conceptual illustration based on plate and membrane theory; it does not predict clinical force or tooth movement. For each study, the lower and upper limits of the bar were obtained by dividing the lowest and highest measured thickness reported in the article by the nominal foil thickness (t/t_0): occlusal thickness after thermoforming for Bucci et al. (0.38–0.69 mm over 0.75 mm) [9]; the regional percentages of preserved thickness measured with micro-CT for Ghoraba et al. (50–85%) [22]; mean thickness by tooth for Tran and Pham 2026a (404–482 µm over 760 µm) [23] and by model base height for Tran and Pham 2026b (268–446 µm over 760 µm) [24]; and the percentages reported directly by Kim and Park (36.5–88.5%) [29].

The cubic relationship should therefore be read as an upper bound and an explanatory device, not as a law that applies to the whole appliance. It derives from classical thin-plate theory, which assumes a flat, homogeneous, linearly elastic plate undergoing small deflections, and an aligner departs from each of these assumptions. It is a doubly curved shell in which bending and membrane actions are coupled; its contact with the crowns is partial and changes as the appliance seats; multilayer foils are not homogeneous through their thickness, so their bending stiffness depends on the modulus and position of each layer relative to the neutral axis rather than on total thickness alone; thermoforming alters the elastic modulus [23]; and the response decays over time [17,24]. What the t^3 term contributes is qualitative: small, regionally variable losses of thickness can produce disproportionate changes in local stiffness, especially where bending predominates. Quantifying that effect in a real aligner requires measured regional thickness and models that include curvature, contact, and viscoelasticity.

The elastic modulus does not remain constant either. Ryu et al. observed that thermoforming modifies the flexural modulus of several commercial foils, and the direction of this change depends on the material and thickness: it increased in some 0.5 mm foils and

decreased in others of 0.75 and 1.0 mm [23]. Therefore, both factors of the equation, E and t, are altered during manufacturing and can do so in opposite directions.

Added to this is the viscoelastic behavior of polymers. In 24-h tests in a humid environment at a controlled temperature, Lombardo et al. recorded a stress relaxation that can exceed 50% of the initial value in the first few hours, plateauing approximately after 8 h; monolayer materials generated the highest absolute stresses, while bilayer materials showed a more constant release with values up to four times lower [24]. Min et al. described force reductions of 10% to 17% after five cycles of repeated loading [17], and Elkholy et al. recorded nonlinear return curves during the derotation of an incisor, which are consistent with this same behavior [7]. Consequently, any initial force measured in the laboratory describes only the moment of insertion. A comparison of thicknesses should ideally be expressed as a load-over-time curve rather than a single value. The time-dependent behavior of aligner materials is particularly relevant when comparing different thicknesses. The included evidence does not establish how stress relaxation evolves over a clinical wearing interval in aligners of different thicknesses made from the same material. Consequently, differences in force observed at insertion may narrow, persist, or widen over time [17,24]. Conclusions based solely on initial measurements characterize the load at insertion rather than the force delivered throughout the wearing interval.

Intraoral use results in slower changes. In retrieved Invisalign aligners worn for about six weeks, Bradley et al. found a lower indentation modulus and hardness and greater creep than in unused aligners [43], whereas Fang et al. found no significant change in elastic modulus or stress relaxation after two weeks of wear, although surface voids and delamination were visible [44]. Under simulated mechanical friction in artificial saliva, aligner materials released microplastic particles after seven days [45], and the amount increased between 7 and 14 days and was associated with material composition [46]. None of these studies compared thicknesses, and they do not show an effect of thickness on force delivery. They do indicate that the material properties assumed in laboratory tests and finite element models are not constant during clinical use, which adds uncertainty to any thickness comparison based on as-received specimens.

4. Synthesis of the Evidence

4.1. Thickness and Initial Mechanical Response

Unless otherwise stated, the force values reported in this section refer to a single tooth, usually a maxillary central incisor mounted on a force–moment sensor, and to the component acting in the direction of the programmed movement. Results obtained using pressure-sensitive films and finite element analyses are reported according to the outcome measures defined by their authors, as these may represent integrated normal loads, calculated forces, displacements, or stresses rather than directly comparable force vectors acting on individual teeth.

Tests on flat foils established the foundations. Kwon et al. compared 0.508, 0.762, and 1.016 mm foils in three-point bending and placed the useful deflection range between 0.2 and 0.5 mm; within this range, the thinnest foil stored and returned more energy than thicker ones of the same brand [3]. Min et al. found a significant interaction between thickness and deflection, which explained the force better than the product or the material [17]. Both works show that a specific force cannot be assigned to a foil based solely on its thickness: activation and loading history condition the response. Being flat specimens, they do not replicate the contact of an aligner with the dentition.

In thermoformed appliances, Hahn et al. compared two materials in two thicknesses (0.8 and 1.0 mm Erkodur; 0.75 and 1.0 mm Biolon) during upper central incisor tipping. Mean horizontal forces ranged between 1.62 and 5.35 N, with intrusive components of

up to 2.47 N; thicker appliances generated significantly higher forces, generally exceeding those considered ideal [4]. Kohda et al., using a force sensor during simulated bodily movement, confirmed within each of three materials (Duran, Erkodur, and Hardcast) that 0.75–0.8 mm foils consistently produced more force than 0.4–0.5 mm foils. Interestingly, a 1.0 mm activation generated significantly less force than a 0.5 mm activation, potentially reflecting permanent deformation or loss of fit at larger activations [8].

Elkholy et al. evaluated thinner commercial PET-G foils. During a simulated 0.25 mm labiopalatal bodily movement of tooth 11, mounted on a three-dimensional force–moment transducer, the 0.5 mm aligner generated median forces of −7.89 N (labial) and 8.37 N (palatal). Compared with the 0.5 mm aligner, the 0.4 and 0.3 mm aligners reduced force magnitudes by approximately 35% and 71%, respectively [6]. In a 10° derotation, moments were 73.6 N·mm with 0.5 mm, 41.1 N·mm with 0.4 mm, and 17.8 N·mm with 0.3 mm [7]. In both studies, the 0.3 mm foil was unstable during manipulation, and the authors proposed a 0.4–0.5–0.75 mm sequence, which has not been clinically validated. Gao and Wichelhaus compared 0.5, 0.625, and 0.75 mm with three gingival margin widths during palatal tipping and intrusion: only the difference between 0.5 and 0.75 mm was significant, and a 0–1 mm margin reduced forces and moments as much as or more than any change in thickness [1].

The distinction between load magnitude and force system is decisive. In the systematic review by Iliadi et al., which included 13 in vitro studies and meta-analyzed two, thicknesses of 0.5, 0.625, and 0.75 mm were not associated with significant differences in the moment-to-force ratio during palatal incisor tipping with a 3–4 mm gingival margin [15]. Increasing stiffness can therefore amplify the load without modifying the movement pattern. Elshazly et al. reached a similar conclusion using finite elements: with foils from 0.3 to 0.6 mm and four margin designs, the resulting force for a 0.2 mm vestibular translation varied between 1.0 and 2.2 N, increasing with thickness and extended straight margins, and all combinations produced uncontrolled tipping [25].

Material composition modulates the effect of thickness. Using pressure-sensitive films, Elshazly et al. observed that 0.75 mm aligners transmitted significantly higher total forces (normal force summed over the pressure films placed on the incisor) than 0.50 mm ones of the same material, and that 0.75–0.89 mm multilayer foils generated less force than 0.75 mm monolayer ones [2]. In other words, a thicker multilayer foil can be less rigid than a thinner monolayer one, meaning thickness is only comparable within the same material.

Finite element models agree on the direction of the effect, but not on its magnitude. Liu and Chen calculated that periodontal ligament stress tripled when going from 0.75 to 1.25 mm [12], while Seo et al., using a validated nonlinear viscoelastic ligament, found only 6% more principal stress with 0.75 mm than with 0.5 mm in lingual inclination, and negligible differences in rotation [13]. Lyu et al., integrating in vitro testing and viscoelastic modeling, found higher stress with 0.75 mm than with 0.50 mm, without a clear relationship between thickness and movement control capability [26]. These discrepancies are largely explained by differences in ligament representation, boundary conditions, contact models, and thickness ranges; thus, figures from different models should not be compared directly. None of these calculated stresses equate to a clinical threshold for ischemia, root resorption, or attachment loss.

Ghoraba et al. linked manufacturing to force transmission. When thermoforming Zendura FLX foils over models ranging from 15 to 30 mm in height, the accumulated normal force on the incisor decreased from 88.9 to 45.7 N, parallel to progressive thinning; the incisal edge retained about 50% of the original thickness, and the gingivovestibular area about 85% [27]. As suggested by Elshazly et al. [2], these pressure film readings represent integrated normal pressure rather than an orthodontic force vector applied to the center of resistance.

4.2. Material Composition and Layer Architecture

Thickness and material are rarely varied independently in the literature. Only some mechanical studies compared different thicknesses of the same foil: Gao and Wichelhaus [1] and Elkholy et al. [6,7] with PET-G, Hahn et al. within each of two materials [4], Kohda et al. within each of three [8], Kwon et al. within each brand [3], and Elshazly et al. for 0.50 and 0.75 mm foils of the same monolayer material [2]. These within-material comparisons provide the strongest basis for attributing observed changes in force to thickness while minimizing confounding effects related to material composition. Comparisons across commercial systems [10,11] or across polymers [23,24] mix thickness with differences in elastic modulus, layer structure, thermoforming behavior, water uptake, and fit, and their results cannot be read as an effect of thickness alone.

Layer architecture adds a second source of variation. Most of the mechanical evidence concerns monolayer PET-G [1,6,7], while thermoforming and morphometric studies increasingly use multilayer foils such as Zendura FLX [2,27–29]. In a layered foil, bending stiffness depends on the modulus and position of each layer, so total thickness is an incomplete descriptor: multilayer foils of 0.75 and 0.89 mm delivered less force than 0.75 mm monolayer foils [2], and bilayer materials showed lower absolute stresses but a steadier release over 24 h than monolayer ones [24]. Directly printed aligners form a third group, whose resins and post-curing protocols differ from those of thermoplastic foils and whose relationship between thickness and force has hardly been studied [34–36].

For these reasons, the analysis was not restricted to a single material or structure, which would have left too few studies for any comparison. Instead, the polymer and layer structure are given for each study in Table 2 where reported, and statements about the effect of thickness in this review rest on within-material comparisons unless otherwise indicated.

4.3. Nominal Thickness, Actual Thickness, and Regional Distribution

The nominal foil thickness does not match the aligner's thickness. In a prospective clinical study with 0.75 mm vacuum-thermoformed PET-G aligners, Bucci et al. measured occlusal thicknesses between 0.38 and 0.69 mm, with good reproducibility between two thermoformings of the same model (maximum Dahlberg error of 0.13 mm) [9]. In 20 Invisalign aligners analyzed by micro-CT, Mantovani et al. recorded mean thicknesses of 0.566 to 0.644 mm, with the only significant difference in the molar region, where the gingivolingual edge was 0.068 mm thinner than the occlusal surface [30]. Lombardo et al. and Palone et al. compared six commercial systems with the same nominal thickness on a single model using micro-CT, finding significant differences in thickness and fit between brands [10,11]. Because the systems also differ in polymer, layer structure, and manufacturing process, these differences cannot be attributed to thickness alone. Both studies originate from the same group and analyze the same systems, so they should not be counted as independent series.

The magnitude of thinning depends on the manufacturing method and parameters. Cupolillo et al. thermoformed the same PET-G foil using three techniques, obtaining mean thicknesses of 467 µm with positive pressure, 429 µm with digital vacuum, and 380 µm with conventional vacuum; the latter also showed the greatest variability [31]. Model height is a critical variable: with 760 µm Zendura FLX foils thermoformed under pressure, Tran and Pham observed the mean thickness drop from 446 µm with a 2 mm base to 268 µm with an 8 mm base [22], aligning with findings by Ghoraba et al. for taller models [29]. In contrast, S et al. found no substantial effect of the thermoforming machine on 0.75 mm PET-G and TPU foils analyzed with nano-CT, except in the molar region [32]. Allaf et al. compared ten brands thermoformed on one or two models simultaneously and measured with a caliper which showed that dual forming produced similar or slightly higher thicknesses, with

significant interaction between brand, region, and number of models [33]. The advantage of calipers is their accessibility, but they only provide point measurements.

The anatomical pattern of thinning is not universal. Palone et al. described lower thicknesses in anterior teeth and gingival/coronal centers than in posterior teeth and occlusal surfaces [11]. With 760 µm multilayer foils, Tran and Pham measured 404 µm in incisors and 482 µm in molars, representing a 36% to 47% loss, with vestibular surfaces systematically thinner than palatal ones [28]. However, Cupolillo et al. observed thicker anterior teeth than the first molar under conventional vacuum [31], and S et al. described thickness increasing from posterior to anterior [32]. The claim that a specific region is always the thinnest therefore lacks general validity. Differences arise from the combination of polymer, forming technique, model height, crown morphology, measurement point location, and statistical treatment of repeated observations.

Comparing studies requires homogeneous reporting of nominal thickness, measured thickness, method (caliper, optical scanner, micro-CT, or nano-CT), anatomical location, and dispersion. An absolute loss in millimeters is not equivalent to a percentage loss when materials start from different thicknesses, and averaging surfaces can obscure mechanically relevant regional minimums. Furthermore, volumetric acquisition by micro-CT does not guarantee full-surface measurement: most studies analyze selected slices or points [10,11,30].

The space between aligner and tooth (gap) is a variable distinct from thickness. Micro-CT analyses document regional differences in fit [10,11,34], although mostly in passive devices. A local gap does not imply an absence of load on the entire crown, as the active aligner generates contacts that shift during insertion. Thickness and fit maps are, in this sense, a morphological starting point that should be linked to simultaneous force and moment measurements.

Evidence on dimensional stability in the mouth is scarce. Bucci et al. found no clinically relevant changes in occlusal thickness after ten days of full-time wear [9]. This result is limited to one material, one thickness, and one protocol, and geometric stability does not imply conservation of elastic properties, which stress relaxation modifies more rapidly [24].

4.4. Directly Printed Aligners

Direct printing eliminates thermoforming and theoretically allows different thicknesses to be assigned to each region. In practice, the deviation reverses its sign. Edelmann et al. SLA-printed aligners designed at 0.5, 0.75, and 1.0 mm, obtaining devices 0.25 to 0.27 mm thicker than the design file—an excess that could not be attributed to the coating used for scanning [35]. McCarty et al. verified that print orientation and post-curing duration barely modified overall accuracy, though localized deviations persisted [36]. In embrasures, Kim and Park measured with micro-CT that thermoformed aligners retained between 36.5% and 88.5% of the foil thickness, while printed ones reached 197% to 470% of the designed thickness; a 0.05 mm offset improved printed fit [34]. The design thickness of a printed aligner thus does not describe the actual device either, and comparing technologies requires measuring both.

4.5. Influence of Thickness According to Movement

Most of the evidence in this section comes from finite element models, which report initial displacements and stresses calculated for a single loading step. A larger calculated displacement or periodontal ligament stress does not mean that a movement will be more effective, more predictable, or safer in the patient, nor that root control will improve; those outcomes can only be established clinically, by comparing planned and achieved movement. The findings below are interpreted with that limitation in mind.

4.5.1. Transversal Movements

In dentoalveolar expansion, Li et al. compared 0.5 and 0.75 mm aligners with seven movement patterns in a finite element model. Greater thickness increased calculated vestibular crown displacement and periodontal stress, but a tipping tendency predominated in all cases; the sequencing pattern (joint, distributed, or alternating movement of premolars and molars) influenced efficiency as much as thickness did [14]. Gómez et al. experimentally measured transverse forces of 60 PET-G aligners of 0.030 and 0.040 inches (0.76 and 1.02 mm) with three margin designs: the combination of greater thickness and a 10 mm extended straight margin generated the highest forces in premolars and molars, and forces decreased from anterior to posterior in all groups [5]. This anteroposterior decrease aligns with the reduced molar expansion efficacy reported in clinical practice.

The only comparative clinical data also comes from the transverse plane. In the trial by Cengiz and Göymen, 0.75 mm aligners produced significantly greater increases in intercanine, interpremolar, and intermolar distances and arch perimeter than 0.5 mm aligners [42] (Section 4.6). Convergence between models, trials, and this clinical outcome supports an increase in transverse load with stiffer designs but does not demonstrate better root control during expansion.

4.5.2. Sagittal Movements: Distalization, Torque, and Retraction

In simulated molar distalization, Cheng et al. compared four thicknesses and four margin morphologies. Increasing thickness raised calculated initial displacement and periodontal stress, while the margin dictated molar inclination and anterior anchorage reactions [18]. Therefore, a greater calculated distal displacement does not equate to a more predictable bodily distalization. Studies reporting only the active molar movement fail to assess overall efficiency without also quantifying reaction teeth.

In torque studies, thickness modifies the compensation needed to achieve a given pattern. In an extraction mass retraction, Cheng et al. calculated that to obtain central incisor translation, the 0.5 mm aligner required a 0.7 mm power ridge, and the 0.75 mm aligner a 0.25 mm one. With the thicker aligner, compensation produced more marked side effects, such as canine intrusion and second premolar mesial tipping, necessitating careful posterior anchorage monitoring [37]. This result illustrates that thickness and compensation geometry must be designed jointly, but it relies on a simulated model and is not a clinical recommendation.

In anterior retraction, Lyu et al. and Alhasyimi et al. reported higher periodontal stress with greater thicknesses [26,38]. Alhasyimi et al., using thicknesses from 0.75 to 1.15 mm and three attachment designs, proposed 0.75–0.85 mm as the most favorable range [38]. This range was defined from calculated periodontal stress in a single model, not from achieved movement, and was not tested for other teeth, regions, or movements; it should not be taken as a recommended thickness for anterior retraction. Jin et al. evaluated a localized thickening of the posterior aligner segment via finite elements and an experimental model with multi-axis transducers, observing a favorable force redistribution on anchorage units, with less mesial tipping of the second premolar [39]. Because the reinforcement incorporated material and modified geometry, its effect cannot be attributed to a simple global thickness increase.

Exploratorily, Kang et al. proposed gradient gingival thicknesses to modulate incisor torque during retraction, describing less undesired lingual inclination in some configurations [40]. As a simulation preprint without peer review or clinical validation, it must be considered a biomechanical hypothesis.

4.5.3. Vertical Movements: Intrusion and Extrusion

Gao and Wichelhaus recorded higher intrusive forces with 0.75 mm than with 0.5 mm during incisor intrusion [1]. Posteriorly, Tosun and Eglenen simulated a programmed 0.2 mm intrusion in premolars and molars using 0.75, 0.95, and 1.15 mm aligners and three attachment configurations. The maximum calculated intrusion of 0.115 mm on the second molar was achieved with 1.15 mm and beveled horizontal attachments; aligner deformation decreased as assembly stiffness increased [41]. Because the effect relied on the combination of thickness and attachment, an optimal thickness independent of auxiliary design cannot be derived here.

Extrusion is the clearest gap in the vertical plane. No experimental, computational, or clinical study included in this review compared aligner thicknesses during programmed extrusion. Secondary extrusion reported in retraction simulations [37,40] cannot be extrapolated to intentional extrusive force, so there is currently no evidence on which to base a thickness choice for this movement.

4.6. Clinical Evidence

Only one randomized clinical trial has compared thicknesses. Cengiz and Göymen assigned 28 patients with Class I malocclusion and mild maxillary crowding to 0.5 or 0.75 mm aligners, vacuum-thermoformed in-office on printed models [42]. Changes were evaluated by superimposing digital models and initial/final cephalograms, while pain and satisfaction were assessed at six time points. The 0.75 mm group achieved significantly greater increases in intercanine, interpremolar, and intermolar widths, and arch perimeter, but reported more pain; satisfaction was higher with 0.5 mm. The trial has notable limitations: a small sample, retrospective registration on ClinicalTrials.gov (NCT06504498), an indication restricted to mild crowding, and outcomes based on dimensional change between start and end rather than accuracy against planned movement. Still, it provides the first clinical evidence that thickness alters the amount of transverse movement achieved, and does so at the cost of greater discomfort.

These results should be interpreted with caution. The trial measured changes in arch dimensions rather than the agreement between planned and achieved tooth movements. Therefore, although 0.75 mm aligners produced greater transverse changes in this population, this does not demonstrate superior movement accuracy. The small sample size and restriction to patients with mild crowding further limit the generalizability of the findings. Patient-reported outcomes are also relevant, as greater pain and lower satisfaction could potentially affect adherence to the prescribed wearing schedule. However, this relationship was not directly established in the trial. Future clinical comparisons should therefore assess not only movement accuracy but also comfort, adherence, and patient acceptability.

Outside this trial, clinical evidence is limited to the dimensional stability study by Bucci et al. [9]. There are no comparative clinical studies on torque, distalization, intrusion, or extrusion with different thicknesses, nor on root resorption or other safety outcomes.

5. Discussion

5.1. An Insufficient Geometric Parameter

Literature converges solidly on one aspect and leaves significant uncertainty on another. With comparable materials and geometries, thickness modifies the initial mechanical response in the expected direction [1,2,4,8]. However, the nominal value does not describe the structure acting in the mouth. Thermoforming preserves between approximately 35% and 90% of the original thickness depending on the region, technique, and model height [9,27–29,34], and direct printing adds material compared to the design [34,35]. Because local bending stiffness scales with the cube of thickness under classical plate theory

(Section 3), these dimensional deviations may have disproportionate mechanical consequences and represent an important source of variability that most comparative studies do not adequately control (Figure 2). Table 3 summarizes the integrated reading of the evidence by domain.

From the perspective of structural mechanics, thickness must be analyzed alongside the post-manufacturing elastic modulus [23], local curvature, margin extension [1,4,25], support location, and behavior over time [24]. The concept of regional functional stiffness summarizes these interactions, provided it is understood as an explanatory construct rather than a variable validated by a single measurement.

5.2. Load Intensity, Movement Pattern, and Clinical Outcome

The relevant question is not only how much the force increases when thickness is increased, but whether its direction and distribution change in the way required by the planned movement. The moment-to-force ratio, the proportion of crown-to-root displacement, the center of rotation, and anchorage reactions describe the initial movement pattern. Available evidence indicates that greater stiffness increases the load without consistently modifying that pattern [14,15,25,26] and that in torque it alters the necessary compensations rather than the control capability itself [37]. On the other hand, the desirable movement depends on the therapeutic objective: translation is not intrinsically superior to controlled tipping when the latter is the clinical goal.

The trial by Cengiz and Göymen introduces an element not captured by laboratory studies: the cost to the patient [42]. If greater thickness achieves more transverse movement but increases pain and reduces satisfaction, the choice ceases to be purely mechanical. None of the thresholds proposed in finite element models can be translated into clinical recommendations because they depend on specific polymers, activations, and assumptions, and because calculated stresses do not equate to tissue damage.

5.3. Uniform Stiffness vs. Regional Modification

Posterior reinforcements and gingival gradients represent a design approach distinct from a uniform thickness increase [39,40]. Their premise is that each region of the aligner fulfills a different function: retention, force application, moment control, or anchorage. Paradoxically, thermoforming already produces a regional stiffness distribution, albeit uncontrolled [11,28,29]. Direct printing could turn this heterogeneity into a design variable, provided the deviation between designed and achieved thickness is reduced and characterized [34–36]. To date, no clinical trial has compared a regional design with a uniform one.

5.4. Established Findings and Open Hypotheses

The available evidence consistently supports four principal findings, although their generalizability depends on the study design and experimental conditions. First, within the same material and geometry, a thicker aligner produces higher initial forces and moments [1,2,4,6–8]. Second, thermoforming reduces and redistributes thickness, whereas direct printing tends to add material relative to the design [9–11,27–35]. Third, thermoplastic materials lose a substantial part of their initial load under sustained or repeated loading [17,24]. Fourth, in the only randomized trial, 0.75 mm aligners produced more transverse expansion and more pain than 0.5 mm aligners [42].

Other statements in this field remain hypotheses: that the cubic amplification of stiffness translates into clinically relevant differences in the load delivered over a wearing interval; that greater thickness improves torque or root control; that thickness ranges proposed from finite-element stress values, such as 0.75–0.85 mm for anterior retraction [38], are optimal

for patients; that regional or gradient stiffness designs improve control [39,40]; and that thick and thin foils of the same material relax at different rates. Table 3 and the conclusions should be read with this distinction in mind.

5.5. Limitations and Research Needs

The center of evidence is dominated by in vitro trials, morphometric studies, and computational models. Heterogeneity affects materials, nominal and measured thicknesses, activation magnitude, margin design, attachments, and outcomes. Some morphological comparisons use few independent units, and the works of Lombardo et al. and Palone et al. share origin and sample [10,11]. Several recent studies use calipers instead of tomography [28,29,33]. This review also has the limitations inherent to its narrative design: the study selection was not based on a registered protocol. No quantitative synthesis was performed, and methodological quality was appraised qualitatively using design-specific criteria rather than a single risk-of-bias instrument applicable to all included studies. The search was limited to two databases and used broad strings without thickness-specific terms; 45 reports could not be retrieved, and two included articles were published in languages other than English or Spanish.

Future studies should follow the complete causal chain in the same device. In order of priority, they should (1) report measured regional thickness, preferably as three-dimensional maps, rather than nominal thickness; (2) characterize the elastic modulus and stress relaxation of the material after thermoforming or printing and after intraoral use; (3) record three-dimensional forces and moments over the full wearing interval, not only at insertion; (4) compare planned and achieved crown and root movement clinically; (5) quantify reactions on anchorage teeth; and (6) include pain, comfort, wear time, and satisfaction as primary outcomes. In comparative studies, material, margin, and auxiliaries should be kept constant, or factorial designs separating their effects should be employed. Three-dimensional thickness maps, rather than a few point measurements, would facilitate relating geometry to the mechanical response, and finite element models should incorporate measured regional thickness rather than nominal thickness.

6. Conclusions

The thickness of the aligner modifies the initial mechanical response, especially the magnitude of forces, moments, and periodontal stresses, but its effect depends on the polymer, layer structure, activation, margin, and auxiliaries. Because local bending stiffness scales with the cube of thickness under classical plate theory, material loss during thermoforming or material excess in direct printing may have disproportionate mechanical consequences. Therefore, a single nominal thickness value is insufficient to characterize the appliance.

For specific movements, current evidence supports changes in load intensity and certain calculated initial displacements, but it does not demonstrate that greater thickness generally improves root control, anchorage, or clinical efficiency. The only randomized clinical trial indicates more transverse expansion with 0.75 mm than with 0.5 mm, at the cost of more pain. Programmed extrusion remains uninvestigated, and regional stiffness designs must be considered experimental.

Until controlled clinical comparisons are available, a universal or movement-specific optimal thickness cannot be recommended. Future research should treat thickness as a measured regional magnitude and integrate it with appliance fit, the force system over time, and clinical outcomes.

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Abbreviations

CT	computed tomography
M/F	moment-to-force ratio
PDL	periodontal ligament
PET-G	polyethylene terephthalate glycol
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QUIN	Quality Assessment Tool for In Vitro Studies
RoB 2	revised Cochrane risk-of-bias tool for randomized trials
SANRA	Scale for the Assessment of Narrative Review Articles
SLA	stereolithography
TPU	thermoplastic polyurethane

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