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# MECHANICAL PROPERTIES OF DIRECTLY 3D-PRINTED ORTHODONTIC ALIGNERS: A NARRATIVE REVIEW

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## ABSTRACT

Direct three-dimensional (3D) printing is an emergping approach to manufacturing orthodontic clear aligners. Unlike conventional thermoforming, which shapes a thermoplastic sheet over a printed dental model, direct printing fabricates the appliance from digital dental data without a physical model. The clinical value of a printed aligner depends not only on its geometric accuracy but also on its ability to deliver appropriate forces, resist deformation, and retain its properties in the mouth. This narrative review summarises the mechanical properties reported for directly printed aligner materials, including elastic modulus, tensile strength, hardness, viscoelastic behaviour, stress relaxation, and shape recovery. It also considers factors that may influence these properties, including resin composition, printing technology, post-curing, temperature, moisture, and intraoral ageing. Available laboratory studies demonstrate substantial variation between resin systems and testing conditions. Some printed materials exhibit shape-memory behaviour and promising recovery characteristics, whereas other studies report pronounced changes in modulus or residual stress under wet or thermally controlled conditions. These findings cannot be generalised to all directly printed aligners because material formulations and manufacturing protocols differ. Furthermore, results obtained from standardised specimens do not necessarily predict the forces delivered by a complete aligner during clinical tooth movement, and clinical data remain limited. Current evidence supports the potential of direct printing but highlights the need for standardised testing, transparent reporting of manufacturing parameters, and longer-term clinical validation.

**KEYWORDS:** 3D printing; direct-printed aligners; orthodontic materials; mechanical properties; stress relaxation; shape-memory polymers.

## 1. INTRODUCTION

Demand for aesthetic orthodontic appliances, such as ceramic brackets, lingual appliances, and clear aligners, has grown steadily in contemporary orthodontics. Clear aligners were developed by Kelsey Wirth and Zia Chishti in 1997; the system received FDA clearance in 1998, and commercial distribution began in 1999 as Invisalign™ (Align Technology), after which other companies followed. Because of their aesthetics and comfort, clear aligners have become an integral part of orthodontic treatment, and more than 27 clear aligner brands are now available on the global market.[1]

Conventional, or thermoformed, aligners are made by heat- and pressure-forming a thermoplastic sheet over a 3D-printed dental model. Common materials include thermoplastic polyurethane (TPU), polyethylene terephthalate (PET), and glycol-modified polyethylene terephthalate (PETG). PETG, which is easier to thermoform than PET without overheating-related problems, is the most commonly used. Thermoformed aligners are not inert: retrieval analyses show that their mechanical and chemical properties change during intraoral use.[2] The thermoforming step itself also alters the sheet material; Ryu et al. found that thermoforming increased water absorption and reduced the tensile and flexural forces of several commercial aligner sheets.[3]

Direct 3D printing has been proposed as a way to avoid these limitations. It may also allow aligners to be produced in the dental office, potentially on the same day, without a dental laboratory. In contrast to the conventional indirect technique, direct printing omits the physical dental model: the aligner is built directly from electronically stored 3D dental data.[4,5] Direct printing also offers finer control over aligner thickness and geometry, although clinical data are still limited and no aligner-specific testing standard yet exists for printed resins.[6,7] The materials also differ, with photopolymer resins predominating.[4] Several fabrication processes have been used for this purpose, including stereolithography, fused deposition modelling, direct pellet–fused deposition, selective laser sintering, multi-jet photo-cured polymer processing, and continuous liquid interface production.[4,5] Vat photopolymerisation methods, including stereolithography (SLA), digital light processing (DLP), and liquid crystal display (LCD) printing, are considered the most suitable for aligners, with DLP favoured for its accuracy and short printing times.[7]

The clinical success of aligners largely depends on the mechanical properties of the resin materials used. Ideal aligner materials should provide sufficient stiffness to deliver controlled orthodontic forces while remaining flexible enough to allow insertion and removal and to resist fracture during clinical use. Mechanical parameters such as elastic modulus, tensile strength, elongation at break, flexural modulus, flexural strength, and surface hardness directly influence force

transmission, dimensional stability, wear resistance, and long-term intraoral durability.[8,9] Because aligner materials are viscoelastic, the force they exert also declines over time through stress relaxation, with the sharpest decline in the first hours of wear.[10] Inadequate mechanical performance may lead to force decay, permanent deformation, reduced treatment efficiency, and compromised patient comfort. Biocompatibility is also a fundamental clinical consideration, as aligner materials remain in prolonged contact with oral tissues, and their cytotoxic potential must be evaluated alongside mechanical performance.[11]

Despite advances in aligner materials and manufacturing technologies, reported mechanical properties of aligner materials, particularly 3D-printed ones, remain difficult to interpret and compare because studies differ in their materials, experimental conditions, testing protocols, and outcome measures. A clear understanding of these factors is essential for interpreting laboratory findings and assessing their relevance to clinical orthodontics.

This narrative review briefly outlines direct printing technologies and materials and then examines the principal mechanical properties of 3D-printed orthodontic aligners, particularly in comparison with thermoformed aligners. It discusses the influence of material composition, manufacturing technique, temperature, moisture, and intraoral ageing on their mechanical behaviour, considers the clinical implications of the available evidence, and identifies limitations in current research and directions for future investigation.

## MATERIALS AND METHODS

### Protocol and Registration

This narrative systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement guidelines.

### Literature Search Strategy

A comprehensive literature search was conducted using the **PubMed / MEDLINE** database to identify relevant studies investigating the mechanical properties of 3D-printed aligner materials. The search focused on scientific publications analyzing mechanical parameters, resin compositions, intraoral aging, and force delivery.

The search query combined Medical Subject Headings (MeSH) terms and free-text keywords using Boolean operators:
("aligner" OR "clear aligners" OR "orthodontic aligner") AND ("mechanical properties" OR "tensile strength" OR "Young's modulus" OR "stress relaxation" OR "viscoelastic") AND ("3D printed" OR "3D printing" OR "direct-printed aligners" OR "additive manufacturing")

### Eligibility Criteria

Studies were selected based on predetermined inclusion and exclusion criteria:

**Inclusion Criteria:**

1. *Study Designs:* Prospective clinical trials, retrospective clinical trials, *in-vitro* experimental research, and Finite Element Method (FEM) studies analyzing clear aligners.
2. *Intervention / Material:* Evaluation of 3D-printed resin aligner materials or direct comparison between 3D-printed and thermoformed aligners.
3. *Outcomes:* Reporting on key mechanical properties (e.g., elastic modulus, tensile strength, stress relaxation, shape memory, hardness, or intraoral aging effects).
4. *Language:* Articles published in English.

**Exclusion Criteria:**

1. Case reports, case series, abstracts, commentaries, narrative editorials, and books.
2. Studies lacking reliable or appropriate statistical analysis.
3. Studies investigating thermoformed aligners exclusively without any reference to 3D printing technologies or direct-printed resins.

### PRISMA 2020 Flow Diagram

*Systematic Review Literature Search Strategy for 3D Printed Aligner Materials*

| | | |
|---|---|---|
| **Identification** | **Records identified from PubMed:**<br>Database Search (n = 142)<br>Keywords: aligner, mechanical properties, 3D printed aligners | **Records removed before screening:**<br>• Duplicate records removed (n = 28)<br>• Ineligible by automation tools (n = 0)<br>• Removed for other reasons (n = 0) |
| **Screening** | **Records Screened**<br>(n = 114) | **Records Excluded after Title/Abstract Screening**<br>(n = 62)<br>• Irrelevant topic / non-orthodontic study |
| **Eligibility** | **Reports Sought for Retrieval**<br>(n = 52)<br>• Reports not retrieved (n = 0)<br>• Reports assessed for eligibility (n = 52) | **Reports Excluded with Specific Reasons**<br>(n = 29 Total):<br>• Case reports (n = 8)<br>• Abstracts, commentaries, editorials (n = 7) |

| | | |
|---|---|---|
| | | • Studies without reliable stat analysis (n = 9)<br>• Non-English language publications (n = 5) |
| **Included** | **Studies Included in Review**<br>(n = 23)<br>• In vitro experimental research & mechanical testing (n = 18)<br>• Prospective & retrospective clinical trials (n = 3)<br>• Finite Element Method (FEM) studies (n = 2) | |

Direct-printed aligner materials are photopolymer-based resins fabricated from digital dental designs. Their behaviour depends on resin formulation, printing method, and post-processing, including curing. These factors influence whether the finished aligner can maintain its shape and provide consistent performance during use.

Direct-printed aligner technology was developed to address the limitations of thermoformed aligners, building on the growing use of 3D printing for dental models. Several resins are now available, among them Tera Harz TC-85 and TA-28 (Graphy Inc., Seoul, Republic of Korea), which are marketed as having shape-memory properties.[9,12,13] In a 2023 review, Bichu et al. identified TC-85 as the only commercially available printable resin that met the biocompatibility, translucency, and mechanical requirements for aligners,[10] which explains why most of the studies discussed below concern this material.

**Tensile Strength and Force Delivery**

Tensile strength describes a material's resistance to breaking when it is pulled under tension. Force delivery refers to the orthodontic force an aligner applies to the teeth as it attempts to produce the planned movement. These concepts are related but are not interchangeable: tensile testing characterises a material, whereas force delivery also depends on aligner geometry, thickness, fit, and the amount of programmed activation.

The ultimate tensile strength is the stress at which the material ruptures, and toughness is the energy absorbed by the material before it ruptures, calculated as the area under the stress–strain curve. Force-measurement studies show how such material differences translate to the finished appliance. Hertan et al. found that direct-printed aligners (TC-85) programmed with 0.1–0.3 mm of tooth movement generated stabilised forces of 0.76–1.57 N, whereas thermoformed aligners generated 4.73–15.04 N.[14] Some in vitro studies of thermoformed aligners have reported forces more than 20 times the physiological range.[15] In an earlier comparison, Jindal et al. found that 0.75 mm aligners printed from Dental LT clear resin were more geometrically accurate than thermoformed Duran aligners and withstood higher maximum loads with low displacement.[16]

Aligner design also affects force delivery. Grant et al. showed that varying the labial and lingual thickness of direct-printed aligners changed the forces and moments on both the target incisor and the adjacent teeth in complex, hard-to-predict ways.[17] The printed thickness may also differ from the design: Edelmann et al. found that stereolithography-printed Dental LT aligners were about 0.25–0.27 mm thicker than their design files, a deviation large enough to affect clinical performance.[18]

Oyonarte et al. compared the direct-printed resins TC-85, TR-07, and TA-28 with two thermoformed materials, Zendura A and Zendura FLX, after immersion in water at 37 °C for up to 14 days.[13] The printed resins lost tensile force in water at body temperature, with the largest decrease within the first hour and stabilisation thereafter, whereas the thermoformed materials remained comparatively stable.

**Ductility and Brittleness**

Ductility is the ability of a material to deform plastically before fracturing, while brittleness describes a tendency to fracture with relatively little deformation. In aligners, these characteristics can affect resistance to cracking during insertion, removal, and function. A material that is too brittle may fracture more readily, whereas excessive deformation may compromise its fit and force delivery.

Neoh et al. compared thermoplastic materials with 3D-printing resins intended for clear retainers and found that the printed resins were generally more brittle and less ductile.[19] Because retainers and aligners are used differently, this finding should be extrapolated to aligners with caution.

**Young's Modulus and Stiffness**

Young's modulus is a measure of the intrinsic stiffness of a material. It reflects the balance between force delivery and flexibility required for effective yet comfortable orthodontic tooth movement.

In the study by Oyonarte et al., changes in Young's modulus closely paralleled the changes in tensile force.[13] After 14 days in water at 37 °C, the modulus of TC-85 fell from approximately 1170 to 290 MPa, that of TR-07 from 1259 to 560 MPa, and that of TA-28 from 1402 to 311 MPa. The thermoformed materials, Zendura A and Zendura FLX, showed no statistically significant change over the same period, owing to their thermoplastic behaviour.

This temperature- and moisture-dependent softening is consistent with the findings of Choi et al., who described the stress-relaxation and shape-memory behaviour of a temperature-responsive photocurable aligner resin.[8] The resulting increase in flexibility may allow direct-printed resins to deliver lower forces at body temperature, closer to the 0.2–2.5 N range often recommended for orthodontic tooth movement.[12,20]

**Hardness and Indentation Properties**

Hardness reflects resistance to localised indentation and provides information about a material's surface or near-surface response. Instrumented indentation methods can also estimate indentation modulus and elastic recovery. Can et al.

examined directly printed TC-85 aligners before and after one week of intraoral service and found no statistically significant changes in Martens hardness, indentation modulus, elastic index, or indentation relaxation index.[21]
The printer used can also matter. Zinelis et al. produced aligners from the same design on five contemporary 3D printers and found statistically significant differences in indentation modulus and elastic index between devices.[22] The Martens hardness of the printed aligners was similar to that of thermoformed PETG aligners and lower than that of Invisalign, whereas their elastic index was lower than that of both thermoformed and Invisalign aligners.

**Effects of Intraoral Ageing**

Intraoral ageing refers to changes that occur while an aligner is exposed to oral conditions over time, including moisture, temperature fluctuations, saliva, and repeated loading. These exposures may alter mechanical behaviour, dimensional stability, and force delivery.
In the study by Can et al., in-house 3D-printed aligners showed no change in mechanical properties after one week of intraoral use.[21] However, the aligners were produced with a single printer and resin, so the result cannot be generalised to other resins or to the full range of printing technologies, such as material jetting, extrusion, DLP, and stereolithography. By contrast, retrieved thermoformed aligners show measurable changes in their mechanical and chemical properties after intraoral use.[2]

**Stress Relaxation and Viscoelastic Behaviour**

Viscoelastic materials show both elastic responses and time-dependent deformation. Stress relaxation occurs when a material held at a fixed deformation gradually loses the stress it initially generated. For an aligner, this time-dependent reduction may affect how much force remains available during wear; the extent of the effect depends on the material and the conditions under which it is tested.
Stress relaxation is also substantial in thermoformed materials. Lombardo et al. found that four thermoformed aligner materials lost 13–44% of their initial stress within 8 h and 18–62% within 24 h at 37 °C in moist conditions, with most of the loss occurring in the first 8 h.[23]
Lee et al. reported that the 3D-printed shape-memory resin TC-85 showed greater stress relaxation at 37 °C than thermoformed PETG, a viscoelastic behaviour that the authors suggested would allow it to apply a light, continuous force.[12] Shirey et al. tested two other printed materials, Material X (EnvisionTEC Inc., Dearborn, MI, USA) and OD-Clear TF (3DResyns, Barcelona, Spain), and found that the residual stress after 2 h at 2% deformation was less than 10% of the initial stress, suggesting that longer tests would show further decay.[20]
Cremonini et al. compared two thermoformed aligners, Zendura FLX (Bay Materials LLC, Fremont, CA, USA) and Duran (SCHEU, Iserlohn, Germany), with two 3D-printed aligners, Tera Harz TC-85 (Graphy Inc., Seoul, Republic of Korea) and a polyamide (PA; Sweden & Martina, Due Carrare, Padova, Italy), in two consecutive 8-h stress-relaxation tests at 37 °C and controlled humidity.[24] TC-85 showed the greatest stress relaxation, losing 90% of its initial force in the first test and 100% in the second. The PA aligners retained force best, with 32% and 23% relaxation, while Zendura FLX (47% and 29%) and Duran (62% and 29%) fell between the two printed materials. Other factors, such as the type of printer, printing conditions, and print quality control, still need to be investigated.

**Shape-Memory Behaviour and Recovery**

Shape-memory polymers are designed to recover a programmed shape in response to a stimulus, often a change in temperature. Atta et al. compared direct-printed and thermoformed aligner materials and reported that TC-85 showed marked shape-memory recovery at oral temperature, which the authors suggested could improve adaptation, reduce force decay and, together with its greater flexibility, allow larger tooth movements per step. Its microhardness was similar to that of thermoformed sheets.[9] These are laboratory findings, and their clinical benefit has not yet been confirmed.

**Factors Affecting Mechanical Performance**

**Resin composition and material formulation**

Direct printing relies on resin systems whose chemistry and network structure influence stiffness, strength, fracture behaviour, water interaction, and viscoelastic response. Most aligner resins are acrylate- or methacrylate-based, and residual monomers left after incomplete curing raise biocompatibility as well as mechanical concerns.[7] Results from one commercial resin cannot be assumed to represent another. Authors should identify the material and manufacturer and disclose relevant formulation information when available.

**Printing and post-curing parameters**

Printing orientation, layer thickness, exposure settings, support placement, washing, and post-curing may affect polymer conversion and final mechanical behaviour. Camenisch et al. printed TC-85 tensile specimens and full-arch aligners in horizontal and vertical orientations on a DLP printer and found no significant differences in yield strength, breaking strength, or indentation properties between orientations.[25] Mattle et al. investigated different post-curing protocols and found that neither heat treatment nor post-curing in a nitrogen atmosphere significantly changed the mechanical properties of 3D-printed resin aligners.[26] Lim et al., however, showed that oxygen in ambient air can interfere with the post-polymerisation of photopolymer resins, leading to incomplete polymerisation and poorer material properties, and evaluated glycerin and vacuum shielding as ways to limit this effect.[27] Oxygen inhibition is a general problem for light-cured resins, because oxygen quenches the free radicals needed for polymerisation.[28] Whether it has a clinically meaningful effect on thin aligner shells remains to be established.

**Temperature and moisture**

Shirey et al. observed material-dependent changes after wet conditioning at 37 °C,[20] while Choi et al. investigated the temperature-responsive behaviour of a shape-memory aligner resin over a range of temperatures relevant to oral use.[8] Studies should report the conditioning medium, duration, and temperature, and whether measurements were taken wet or after drying.

**Table 1. Summary of key studies on directly 3D-printed aligner materials**

| Study | Materials compared | Test and conditions | Main findings |
|---|---|---|---|
| Choi et al. (2025)[8] | Temperature-responsive photocurable aligner resin | Mechanical and viscoelastic testing across oral temperature range | Softening and stress relaxation at body temperature; shape-memory behaviour |
| Atta et al. (2024)[9] | TC-85 vs thermoformed sheets | Physicochemical and mechanical characterisation | Marked shape recovery at oral temperature; microhardness similar to thermoformed sheets |
| Lee et al. (2022)[12] | TC-85 vs PETG | Thermomechanical testing, stress relaxation and shape recovery at 37 °C | Greater stress relaxation than PETG; light, continuous force; good shape recovery |
| Oyonarte et al. (2026)[13] | TC-85, TR-07, TA-28 vs Zendura A, Zendura FLX | Tensile testing after 37 °C water immersion for up to 14 days | Printed resins lost most force within 1 h; modulus of TC-85 fell from ~1170 to ~290 MPa; thermoformed materials stable |
| Hertan et al. (2022)[14] | TC-85 vs thermoformed aligners | Force measurement with 0.1–0.3 mm programmed movement | Printed 0.76–1.57 N vs thermoformed 4.73–15.04 N |
| Jindal et al. (2019)[16] | Dental LT resin (0.75 mm) vs thermoformed Duran | Geometric accuracy and compressive loading | Printed aligners more accurate and withstood higher maximum loads |
| Grant et al. (2023)[17] | Direct-printed aligners of varying labial/lingual thickness | Forces and moments during incisor lingual movement | Thickness changes altered forces and moments on target and adjacent teeth |
| Edelmann et al. (2020)[18] | SLA-printed Dental LT aligners (0.5–1.0 mm designs) | Micro-scale thickness analysis vs design file | Printed aligners ~0.25–0.27 mm thicker than designed |
| Neoh et al. (2025)[19] | Thermoplastic materials vs 3D-printing resins (retainers) | Physical, mechanical and optical testing | Printed resins more brittle and less ductile |
| Shirey et al. (2023)[20] | Material X, OD-Clear TF vs thermoformed aligners | Tensile and stress-relaxation testing; wet conditioning at 37 °C | Residual stress <10% after 2 h at 2% strain; material-dependent changes |
| Can et al. (2022)[21] | In-house printed TC-85 aligners | Instrumented indentation before and after 1 week in vivo | No significant change in hardness, indentation modulus or relaxation indices |
| Zinelis et al. (2022)[22] | Same aligner design printed on five 3D printers | Instrumented indentation testing | Significant differences between printers; hardness similar to thermoformed PETG |
| Cremonini et al. (2024)[24] | TC-85, polyamide vs Zendura FLX, Duran | Two consecutive 8-h stress-relaxation tests at 37 °C, controlled humidity | Relaxation: TC-85 90%/100%; PA 32%/23%; FLX 47%/29%; Duran 62%/29% |
| Camenisch et al. (2025)[25] | TC-85 printed horizontally vs vertically (DLP) | Tensile and instrumented indentation testing | No significant effect of printing orientation |
| Mattle et al. (2024)[26] | 3D-printed resin aligners | Post-curing with heat treatment or nitrogen atmosphere | No significant effect on mechanical properties |
| Migliorati et al. (2024)[29] | In-office printed TC-85 aligners (16 patients) | Prospective clinical pilot study of movement accuracy | Accuracy: torque 68%, tip 64%, rotation 72%; one case of lip swelling |

**Clinical Implications and Evidence Limitations**

The mechanical properties of directly printed aligners are promising but heterogeneous. Modulus and strength describe aspects of material response, while stress relaxation and creep describe time-dependent behaviour. No single measurement can fully predict clinical performance. A clinically relevant evaluation should ideally combine material-level tests with force measurements on complete aligners, realistic wet and thermal conditioning, repeated insertion and removal, and longer-term intraoral observation.

Clinical evidence is still limited. In a prospective pilot study of 16 patients treated with in-office printed TC-85 aligners, Migliorati et al. reported mean accuracies of 68% for torque, 64% for tip, and 72% for rotation, which the authors considered comparable to those reported for other aligner systems.[29] One patient developed upper-lip swelling, possibly because of incomplete resin curing, which underlines the link between post-processing and both the mechanical and biological performance of printed aligners.

Several limitations recur in the literature: small sample sizes, differences in specimen geometry, inconsistent conditioning protocols, limited reporting of printing and post-curing parameters, short ageing periods, and comparisons between different resins. Much of the available evidence also concerns a single commercial resin, TC-85. Findings from in vitro experiments should not be presented as proof of improved clinical outcomes unless supported by appropriate clinical evidence. Potential commercial or manufacturer affiliations should also be considered when interpreting studies of proprietary materials.

This review has limitations of its own. It is a narrative rather than a systematic review, it was based on a single database, and it did not include a formal risk-of-bias assessment, so the selection of studies may be incomplete.

**Future Directions**

Future research should establish standardised protocols for tensile, flexural, indentation, creep, and stress-relaxation testing of printed aligner materials. Studies should report resin identity, printer model, print orientation, layer thickness, washing and post-curing conditions, specimen dimensions, temperature, hydration, and statistical uncertainty. Direct comparisons would be more informative if materials were tested under matched conditions and if both standardised specimens and complete aligners were evaluated. Larger and longer-term clinical studies are also needed to determine whether laboratory differences meaningfully affect force delivery, aligner durability, tracking, and treatment outcomes.

## CONCLUSION

Direct 3D printing has expanded the material and design options available for orthodontic aligners. Published studies demonstrate that mechanical behaviour, including stiffness, tensile strength, hardness, stress relaxation, and shape recovery, varies considerably between resin systems and can be affected by moisture, temperature, the printer used, post-curing, and intraoral ageing. Shape-memory materials offer promising opportunities, but their laboratory behaviour should not be equated directly with clinical superiority. At present, the evidence is best interpreted as material-specific and protocol-dependent. Standardised testing and longer-term clinical validation are required before robust conclusions can be drawn about the clinical performance of directly printed aligners.

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