ORIGINAL RESEARCH PAPER
Volume - 15 | Issue - 09 | September - 2026 | PRINT ISSN No. 2277 - 8179 | DOI : 10.36106/ijsr
INTERNATIONAL JOURNAL OF SCIENTIFIC RESEARCH

THREE-DIMENSIONAL (3D) PRINTING IN ORTHODONTICS: A COMPREHENSIVE REVIEW OF CURRENT APPLICATIONS, MATERIALS, AND FUTURE DIRECTIONS

Orthodontics

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ABSTRACT

3D printing has quietly become a workhorse of modern orthodontic practice. Plaster models and hand-fabricated transfer trays are steadily being replaced by a digital pipeline running from an intraoral or CBCT scan to a printed appliance. This review covers the technologies, materials, clinical applications, and gaps that remain. Two technologies-stereolithography (SLA) and digital light processing (DLP)-lead the way for printing orthodontic resins. Fused deposition modeling (FDM) is a cheaper option but less precise. Material jetting and metal 3D printing (selective laser melting/sintering) are used less often, mainly for highly detailed models and metal parts. Printed study models, indirect bonding trays, retainers, surgical/miniscrew guides, and orthognathic splints are well established, while direct-printed clear aligners in shape-memory resins and early custom-printed brackets and 4D 'smart' auxiliaries represent the newer edge of the field. The main challenges aren't really about the printing itself - they're about everything around it: testing materials properly for safety, understanding how well they hold up over time, inconsistent regulations, and the cost and training needed to adopt these tools. AI-assisted design, wider shape-memory adoption, and more in-office printing are likely to push the field further, though larger long-term trials are still needed.

KEYWORDS

3D printing; additive manufacturing; orthodontics; clear aligners; stereolithography; digital workflow; surgical guides

INTRODUCTION

Orthodontics has been going digital for roughly two decades, driven by intraoral scanning, CBCT, CAD/CAM, and additive manufacturing converging into one workflow.[1,2] 3D printing closes the loop- turning a virtual treatment plan into something placeable in a patient's mouth. It started as a way to print study models instead of pouring plaster, and has since grown to cover indirect bonding trays, retainers, clear aligners, surgical/miniscrew guides, orthognathic splints, and increasingly, custom brackets and functional appliances.[3,4]

The appeal is straightforward: every appliance is built to a patient's exact anatomy without the labor cost of custom work, and digital files can be stored and reprinted rather than kept as plaster casts. But the shift to additive manufacturing has also raised questions around resin biocompatibility, accuracy, durability, cost, and regulatory pathways. This review covers the technologies, materials, and clinical applications of 3D printing in orthodontics, summarizes reported accuracy and performance, and outlines the main limitations and emerging directions.

Evolution and Principles of 3D Printing Technology

The Digital Orthodontic Workflow

A digital-to-print workflow runs through four stages: data acquisition (intraoral scan, desktop scan, or CBCT for tissue detail); digital design, where the STL/DICOM file is processed in CAD software to plan tooth movement or appliance geometry; the print itself, sliced and built layer by layer; and post-processing-washing, curing, support removal, polishing. Each stage can introduce error that carries forward, so end-to-end workflow validation matters as much as any single step, though it gets little attention in the literature.

Additive Manufacturing Technologies Relevant to Orthodontics

The ASTM/ISO 52900 standard groups 3D printing methods into seven broad categories, but orthodontics really only relies on four of them: vat photopolymerization (which includes SLA and DLP), material extrusion (FDM/FFF), material jetting (PolyJet), and powder bed fusion (SLS/SLM/DMLS).[1,9] They cure or fuse material differently, which drives the differences in resolution, cost, and compatible materials-and that decides what each is used for clinically. Table 1 summarizes them.

Table 1. Additive manufacturing technologies used in orthodontics

Technology	Principle	Common materials	Orthodontic uses	Key limitations
SLA	UV laser cures resin layer-by-layer	Photopolymer resins	Models, IDB trays, retainers, aligner molds	Slow at volume; resin cost
DLP	Projector cures a full layer at once	Photopolymer resins	Surgical/implant guides, models	Resolution limited by pixel size
FDM/FFF	Heated filament extruded layer-by-layer	PLA, ABS, PETG	Low-cost models, prototypes	Lower resolution; visible layer lines
Material Jetting	Photopolymer droplets jetted, UV-cured	Multi-material resins	High-fidelity, multi-tissue models	High cost
SLS/SLM/DMLS	Laser sinters/ melts powdered material	Co-Cr, titanium alloys	Custom brackets, expander frames	High capital cost; post-processing

Clinical Applications of 3D Printing in Orthodontics

3D printing now touches almost every stage of orthodontic care.

Diagnostic and Study Models

Study models are by far the most researched application of 3D printing in orthodontics. They were the first thing dental labs started printing, and because of that, they've become the benchmark other applications get measured against for accuracy.[9,10] SLA, DLP, and material jetting typically produce models accurate to well under a millimeter. Note that 'acceptable accuracy' isn't fixed-it depends on what the model is being used for. Orthodontic work generally allows for a bit more tolerance than prosthodontic work

Indirect Bonding Trays

Instead of building a wax/silicone transfer tray over a plaster set-up, bracket positions are planned digitally and a printed tray carries them to the teeth. This shortens chairside and lab time, and placement can be reviewed on-screen before printing.[3]

Clear Aligners

Aligners have traditionally been made indirectly: a series of models is printed, and thin plastic sheets are heated and molded over each one to create the aligners. A newer approach, direct printing, skips that heating/molding step entirely and prints the aligner as a finished product. This has moved from an experimental idea to an early commercial reality, using special shape-memory, body-safe resins designed for wear inside the mouth.[6,7]

The advantages of direct printing: the shape comes out more consistent, the material doesn't get weakened by the heating process, and manufacturers can vary the thickness or build in features that apply targeted force to specific teeth.[7]

Retainers

Retainers follow the same pattern-vacuum-formed over a printed model, or printed directly in flexible resin. The main practical upside is archiving: a saved file means a lost or broken retainer can simply be reprinted, no new impression needed.

Auxiliary and Functional Appliances

A growing tail of auxiliary devices-space maintainers, expanders, functional frameworks, occlusal splints-is now being printed too. Recent reviews flag these as understudied relative to aligners yet among the faster-growing corners of the field, particularly with shape-memory ('4D-printed') materials that respond to intraoral temperature or moisture, potentially adjusting a device's geometry over treatment3 without intervention.[4]

Custom Brackets and Metal Components

SLM/DMLS can build custom bracket bases or expander frameworks in cobalt-chromium or titanium, layer by layer, instead of casting or milling. This is the least mature application here-biomaterial choice, workflow standardization, and clinical implications are still being worked out.[8]

Surgical Guides and Orthognathic Splints

Virtual surgical planning combined with a printed guide or splint is used for miniscrew/TAD placement and orthognathic surgery wafers. SLA and DLP guides show drill-sleeve deviations of roughly 0.1–0.3 mm, well within a safe margin even after sterilization, with DLP usually — not always — edging out SLA.[10] For orthognathic models specifically, SLA beats PLA-based FDM on dimensional accuracy, though both fit the splint clinically.[9]

Materials Used in Orthodontic 3D Printing

Material choice comes down to application, mechanical demands, and — for anything intraoral — biocompatibility. Photopolymer resins dominate vat-photopolymerization printing across models, IDB trays, guides, and now direct-printed aligners and retainers; shape-memory and elastomeric formulations suit flexible appliances, rigid resins serve models and guides.[7] PETG remains the workhorse for indirect aligner fabrication given its strength, clarity, and biocompatibility record.[6] Metal components rely on cobalt-chromium and titanium via powder-bed fusion.[8] A recurring issue is inconsistent ISO 10993-5/-12 cytotoxicity reporting, making biocompatibility claims hard to compare across studies.

Accuracy and Clinical Performance

Accuracy splits into trueness (closeness to the digital file) and precision (repeatability) — the most commonly reported outcome in this literature. The general order across studies is DLP and material jetting on top, SLA close behind, FDM trailing.[9,10] Numbers swing with printer model, orientation, layer thickness, resin batch, and post-processing, so cross-study comparisons need caution — but mainstream technologies generally stay within acceptable limits for orthodontic use, with prosthodontic-grade tolerances the main reason to reach for higher-end DLP, PolyJet, or a well-calibrated SLA setup.[9]

Advantages of 3D Printing in Orthodontic Practice

- Every appliance is built to the patient's own anatomy, without the extra labor bespoke work would cost.
- No plaster pouring or cast storage; digital indirect bonding also cuts chairside and lab time.[3]
- Files can be archived and reprinted on demand — handy for a lost or broken retainer.
- In-office printing can bypass the external lab, shortening turnaround and lowering cost at volume.
- CAD-driven design allows features impractical by hand — variable thickness, force-delivery zones, lattices.
- Better-fitting appliances mean fewer chairside adjustments and more comfortable treatment.

Limitations and Challenges

- Cytotoxicity assessment of intraoral resins remains inconsistently documented, with limited evidence on their long-term biocompatibility, particularly for directly printed aligners and retainers.[6,7]
- The long-term performance of these materials under repeated cyclic loading, temperature fluctuations, and prolonged exposure to saliva requires further investigation through extended follow-up studies.
- The high initial investment required for printers, post-processing equipment, specialized resins, and software licenses may pose financial challenges, particularly for smaller dental practices.
- Adequate training is required for clinicians and dental teams in digital scanning, appliance design, printing, and post-processing, as errors at any stage may be transferred unnoticed to the final appliance.
- Regulatory frameworks vary across countries, and the rapid introduction of novel printing materials has, in some cases, progressed faster than the development of appropriate regulatory standards.
- Current evidence is predominantly based on in-vitro studies, accuracy assessments, and small case series, while large-scale, long-term clinical trials comparing 3D-printed appliances with conventional alternatives remain limited.[5]
- The use of uncured resin, alcohol-based cleaning agents, and disposable printed models also introduces additional waste-management and environmental concerns that are less prominent in conventional workflows

Emerging Trends and Future Directions

Emerging developments include shape-memory or "4D printing" materials that respond to intraoral temperature or moisture and may reduce the number of aligner stages required.[4] AI-assisted design is increasingly being integrated into treatment-planning software, enabling faster appliance design and staging. Direct-printed aligners are progressing toward wider clinical adoption as biocompatible resins overcome regulatory and safety challenges, potentially reducing costs compared with conventional thermoformed aligners.[6,7] Metal 3D printing for brackets and expander frameworks remains at an earlier stage but is expected to advance with improvements in printing workflows and biomaterial standards.[8]

CONCLUSION

3D printing has expanded beyond study models to include aligners, retainers, indirect bonding trays, auxiliary appliances, custom metal components, and surgical/miniscrew guides. SLA and DLP provide a practical balance of accuracy and efficiency, while FDM, material jetting, and powder-bed fusion serve lower-precision or specialized applications. Despite generally acceptable accuracy, wider adoption is limited by inconsistent biocompatibility testing, insufficient long-term evidence, cost, and evolving regulatory standards. With advances in materials, software, and in-office printing, 3D printing is likely to become increasingly integral to orthodontic practice.

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