International Journal Dental and Medical Sciences Research
Volume 8, Issue 5, Sep.-Oct 2026 pp: 112-118 www.ijdmsrjournal.com ISSN: 2582-6018

4D Printing in Prosthodontics: Smart Materials, Emerging Applications, Current Challenges and Future Perspectives

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Date of Submission: 21-09-2026 Date of Acceptance: 02-10-2026

ABSTRACT:
Additive manufacturing has transformed dental fabrication by enabling digitally planned, patient-specific structures. Three-dimensional (3D) printing, however, generally produces static objects whose geometry and properties remain largely unchanged after fabrication. Four-dimensional (4D) printing extends additive manufacturing by incorporating a programmed time-dependent response, usually through stimuli-responsive materials or architectures. This narrative review summarizes the principles of 4D printing, major smart-material systems, stimulus-responsive mechanisms, manufacturing considerations and emerging prosthodontic applications. Shape-memory polymers, hydrogels, elastomeric systems and responsive composites can respond to temperature, moisture, pH, light or externally applied fields. Potential dental applications include adaptive denture components, removable prosthodontic components, implant-related systems, maxillofacial prostheses, controlled drug delivery and tissue-engineering constructs. Most reported applications remain experimental or preclinical. Important barriers include mechanical fatigue, dimensional instability, biocompatibility, uncontrolled activation, manufacturing variability and the absence of standardized testing. Future research should focus on clinically relevant responses, materials specifically designed for the oral environment, reproducible manufacturing and longitudinal evaluation under realistic mechanical, thermal, chemical and biological conditions.

Keywords: 4D printing; additive manufacturing; smart materials; shape-memory polymers; prosthodontics; digital dentistry; stimuli-responsive materials

I. Introduction

Computer-aided design and computer-aided manufacturing (CAD/CAM) have progressively changed prosthodontic fabrication. Digital impressions, virtual design and computer-controlled manufacturing have improved customization and reproducibility, while additive manufacturing has made it possible to produce complex geometries with efficient material use. [16–18]

The principal limitation of conventional 3D printing is that the printed object is generally static. Once fabrication and post-processing are completed, the geometry and material characteristics are expected to remain stable. Four-dimensional printing introduces time as an additional design variable. A 4D-printed structure is produced so that its geometry or functional properties can change in a predetermined manner after exposure to an appropriate stimulus. [1–3]

This concept is particularly relevant to dentistry because the oral cavity is dynamic. Prostheses experience changes in temperature, moisture, pH, mechanical loading and chemical exposure. A responsive material could therefore provide controlled adaptation or functional change that cannot be achieved with a purely static structure. Nevertheless, the distinction between technical feasibility and clinical usefulness is important. A material demonstrating shape recovery in a laboratory does not automatically provide a safe or beneficial prosthodontic function.

II. Concept and Principles of 4D Printing

The basic 4D-printing workflow comprises digital design, additive fabrication, programming and stimulus-induced transformation. Unlike conventional 3D printing, the geometry produced during fabrication may represent an intermediate state rather than the final functional configuration. [2,3]

Shape-memory behavior is one of the most established mechanisms. A temporary shape is programmed into a material and later recovered toward a predetermined configuration after activation. Other systems use differential swelling, contraction or changes in stiffness, permeability or

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surface characteristics. Multi-material printing can further create spatially different responses, allowing bending, folding or localized transformation. [5–7]

For prosthodontics, the transformation must be controlled in magnitude, timing and direction. Excessive or unpredictable movement could compromise tissue health, retention, occlusion or mechanical integrity. Therefore, a clinically meaningful 4D system should demonstrate reproducible transformation while maintaining adequate strength, dimensional stability and biological safety over the intended service period

III. Smart Materials for 4D Printing

Shape-memory polymers (SMPs) are among the most widely investigated materials because their deformation can be programmed and subsequently recovered. Thermal activation is common, although moisture and light-responsive systems have also been explored. The clinical relevance of an SMP depends strongly on its transition temperature and mechanical behaviour.

A material activated well above intraoral temperature may require an external trigger, whereas one with a transition range close to oral conditions could risk unintended activation. [5,6,14]

Hydrogels are three-dimensional polymeric networks capable of absorbing water and undergoing swelling or deswelling. Their tunable response has made them attractive for tissue engineering and drug delivery. However, high water content can reduce mechanical strength and produce dimensional instability during prolonged oral exposure. [9,12]

Elastomers and responsive composites can provide larger reversible deformation or combine actuation with reinforcement. Shape-memory alloys and liquid-crystal elastomers have also been investigated in broader 4D-printing research. [3,7] For prosthodontics, material selection represents a balance between responsiveness and durability. The most useful material is unlikely to be the one showing the greatest deformation; rather, it should provide a predictable response while retaining mechanical, dimensional and biological stability.

FIGURE 1: Concept of 4D printing: digital design → smart-material printing → programming → stimulus → transformation.

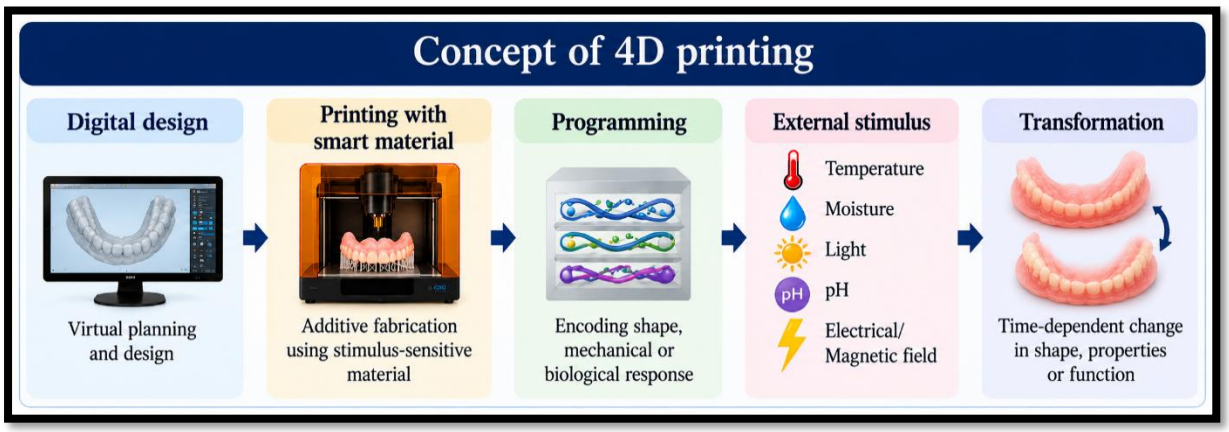

TABLE 1: Comparison of Conventional Manufacturing, 3D Printing, and 4D Printing in Prosthodontics

CONCEPT	MANUAL/ SUBTRACTIVE	ADDITIVE, LAYER-BY-LAYER	ADDITIVE + TIME-DEPENDENT RESPONSE
STRUCTURE	Static	Static	Dynamic
CUSTOMIZATION	Moderate	High	High
SMART MATERIAL	Not required	Not essential	Important
POST-FABRICATION RESPONSE	Minimal	Usually, absent	Programmed
STIMULUS	Not required	Not required	May be required

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SHAPE CHANGE	None	None	Programmed
COMPLEXITY	Variable	Moderate	High
CLINICAL STATUS	Established	Established	Emerging

IV. Stimuli and Transformation Mechanisms

Temperature, moisture, pH, light, electrical fields and magnetic fields are among the stimuli investigated for responsive materials. [2,3,8]

Thermal stimulation is especially important for SMPs. A material can recover toward its programmed shape when its transition temperature is reached. For an intraoral device, however, the activation range must avoid unintended changes during eating and drinking. Moisture-responsive materials are also relevant because saliva is continuously present. Hydrophilic networks can swell, bend or change dimensions, but uncontrolled activation may occur before the prosthesis reaches its intended position.

pH-responsive systems alter ionization, swelling or molecular conformation and may be more useful for localized drug release than for large-scale prosthetic shape change. Light-responsive materials offer spatial and temporal control, although penetration and tissue safety limit their direct intraoral use. Electrical and magnetic systems can provide remote activation and may have future relevance to implant-related or drug-delivery systems, but these approaches remain largely experimental. [2,3,8,12]

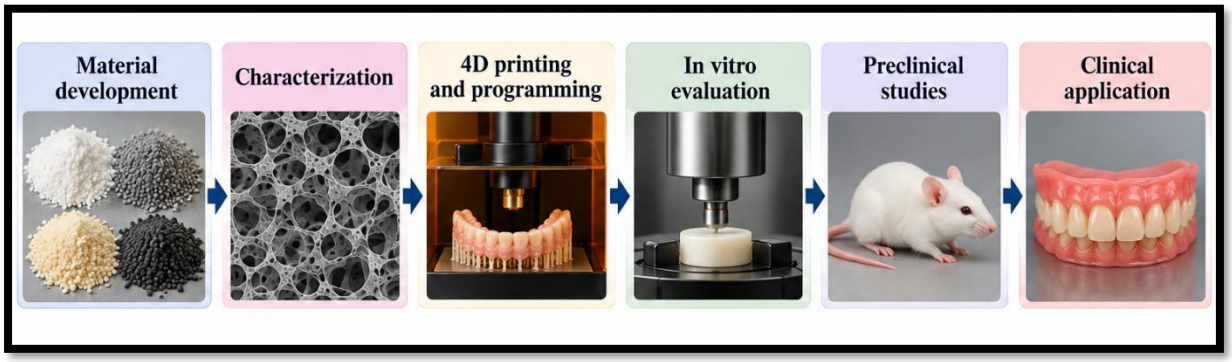

Figure 2: Smart materials and stimulus-responsive mechanisms relevant to 4D printing.

V. Printing and Manufacturing Considerations

Extrusion-based printing, stereolithography, digital light processing and material jetting have all been explored for responsive structures. Extrusion printing can accommodate polymers and hydrogels and can support multi-material deposition, although nozzle dimensions and shear effects may influence performance. Vat photopolymerization offers high spatial resolution and is particularly relevant to digital dentistry, but photopolymer chemistry, residual components and post-curing conditions must be compatible with the intended responsive behaviour. [17,18]

Multi-material printing is particularly important because a prosthesis may require rigid regions for support and compliant regions for controlled transformation. Printing orientation, layer thickness, degree of polymerization, infill pattern and post-processing can influence the final response. Thus, printing a material with smart properties is not necessarily equivalent to producing a clinically meaningful 4D device. The architecture must deliberately encode the desired transformation. [7,8]

Future studies should report printing parameters, stimulus conditions, transformation time, recovery ratio, dimensional accuracy and the number of successful response cycles. Consistent reporting would make comparisons between studies more meaning

VI. Emerging Applications in Prosthodontics

Complete dentures are traditionally static despite changes in residual ridge anatomy and mucosal conditions. A responsive denture component could theoretically provide controlled adaptation, but the material must preserve retention, stability, occlusion, fracture resistance and biocompatibility.

Removable prosthodontic components may be another opportunity. A component capable of temporary deformation during insertion followed by recovery could simplify placement or improve retention. Repeated insertion and removal, however, would require stable mechanical behaviour and resistance to fatigue.

Direct application of 4D printing to definitive crowns and fixed partial dentures is less established because these restorations require high dimensional stability, wear resistance, fracture resistance and color stability. Responsive auxiliary components or adaptive interfaces may be more realistic applications.

Implant prosthodontics offers opportunities for responsive coatings, drug delivery and tissue-engineering interfaces. A near-term approach may involve a responsive component associated with the implant environment rather than a completely shape-changing implant prosthesis.[3,10,12]

Maxillofacial prostheses may benefit from controlled changes in compliance or geometry because they interact with dynamic soft tissues. However, ultraviolet exposure, temperature, moisture and repeated deformation create additional demands for color stability, fatigue resistance and dimensional stability.

4D systems may also support controlled drug delivery and tissue engineering. Stimulus-responsive matrices can potentially regulate the timing or location of therapeutic release, while responsive scaffolds may alter architecture or mechanical characteristics during tissue formation. These applications remain predominantly experimental[10–13]

VII. Current Evidence and Critical Appraisal

The evidence base for 4D printing in dentistry is growing but remains heterogeneous. Studies vary in material composition, printing technique, stimulus conditions and outcome measures. Much of the literature demonstrates technical feasibility rather than a confirmed clinical benefit.[2,3,17]

A major limitation is the difference between controlled laboratory conditions and the oral environment. Saliva, temperature cycling, pH variation, mastication, microbial exposure and cleaning procedures may alter the response over time. Mechanical testing also needs to incorporate repeated activation and fatigue because a clinically useful device may experience many transformation cycles.

Terminology is another issue. Some reports use the term 4D printing for any 3D-printed smart material, even when the transformation has not been deliberately programmed into the printed architecture. Clearer definitions and standardized evaluation would improve scientific consistency. At present, the available evidence supports 4D printing as an emerging research platform rather than a routine clinical technology.

VIII. Barriers to Clinical Translation

The principal challenge is balancing responsiveness with mechanical strength. Increasing molecular mobility may facilitate transformation but reduce stiffness or resistance to deformation, whereas excessive cross-linking or reinforcement can restrict shape recovery. Repeated activation may cause microcracking, interfacial failure or progressive loss of recovery capacity. [2,3,7]

Dimensional stability is equally important. A clinically useful material must respond when intended but remain stable during incidental exposure to saliva, temperature fluctuations and routine chemical conditions. Residual monomers, photo initiators, degradation products and nanoparticles also require biological evaluation. [17]

Manufacturing reproducibility remains another concern. Small variations in layer thickness, orientation, polymerization and post-curing can alter transformation. Multi-material systems add further complexity because differences in adhesion and shrinkage may influence deformation. Standardized testing should include dimensional accuracy, shape-fixity and recovery, transformation time, cyclic stability, fatigue, water sorption, chemical aging, cytotoxicity and microbial interaction.

Finally, clinically relevant in vivo and long-term studies are limited. Responsive systems incorporating drugs, biologically active molecules or cells may also require additional regulatory consideration. These factors mean that successful material transformation alone is insufficient evidence for clinical adoption.

Table 2: Classification of Stimuli-Responsive Systems and Their Dental Relevance

Stimulus	Response	Dental relevance	Main concern
Temperature	Shape recovery / expansion	Adaptive components	Unintended activation
Moisture	Swelling / deformation	Oral-responsive systems	Dimensional instability

pH	Swelling / drug release	Therapeutic systems	Variable oral pH
Light	Photochemical change	Controlled activation	Limited penetration
Electrical field	Shape/property change	Smart devices	External energy needed
Magnetic field	Remote actuation	Implants / drug delivery	Safety & complexity
Chemical stimulus	Molecular / volumetric change	Therapeutic systems	Biocompatibility

IX. Future Perspectives

Future research should move from demonstrating that a material can respond to determining whether that response provides a clinically useful function. Materials should be specifically engineered for the oral environment, with transition temperatures, water responsiveness and mechanical properties matched to prosthodontic requirements.

Multi-material printing may allow selective responsiveness, with rigid regions providing support and compliant regions providing controlled adaptation. Integration with intraoral scanning and CAD could permit patient-specific programming of both initial geometry and subsequent transformation. Finite element analysis and material models may eventually help predict transformation before fabrication.

For complete dentures, controlled adaptation may be more clinically meaningful than large shape changes. In maxillofacial prosthodontics, responsive compliance could help accommodate changing soft-tissue conditions. In implant dentistry, responsive coatings and controlled drug delivery may have greater near-term relevance than fully shape-changing prostheses. [3,10–13]

A useful framework for future studies is to progress through five levels: material response; manufacturing accuracy; mechanical durability; environmental stability; and biological and clinical performance. This staged approach can prevent premature movement from laboratory proof-of-concept to human application.

Table 3. Potential Applications of 4D Printing in Prosthodontics and Their Current Evidence

Application	**4D Function**	**Potential Benefit**	**Evidence**
Complete dentures	Controlled adaptation	Improved tissue conformity	Experimental
Removable components	Reversible deformation	Easier insertion/retention	Experimental
Fixed prosthodontics	Responsive components	Functional adaptation	Early experimental
Implant systems	Responsive coatings/components	Drug delivery / biological modulation	Preclinical
Maxillofacial prostheses	Shape/compliance adaptation	Improved tissue interaction	Experimental
Drug-delivery systems	Stimulus-dependent release	Localized therapy	Preclinical
Tissue-engineering scaffolds	Dynamic structural response	Adaptation during tissue formation	Preclinical

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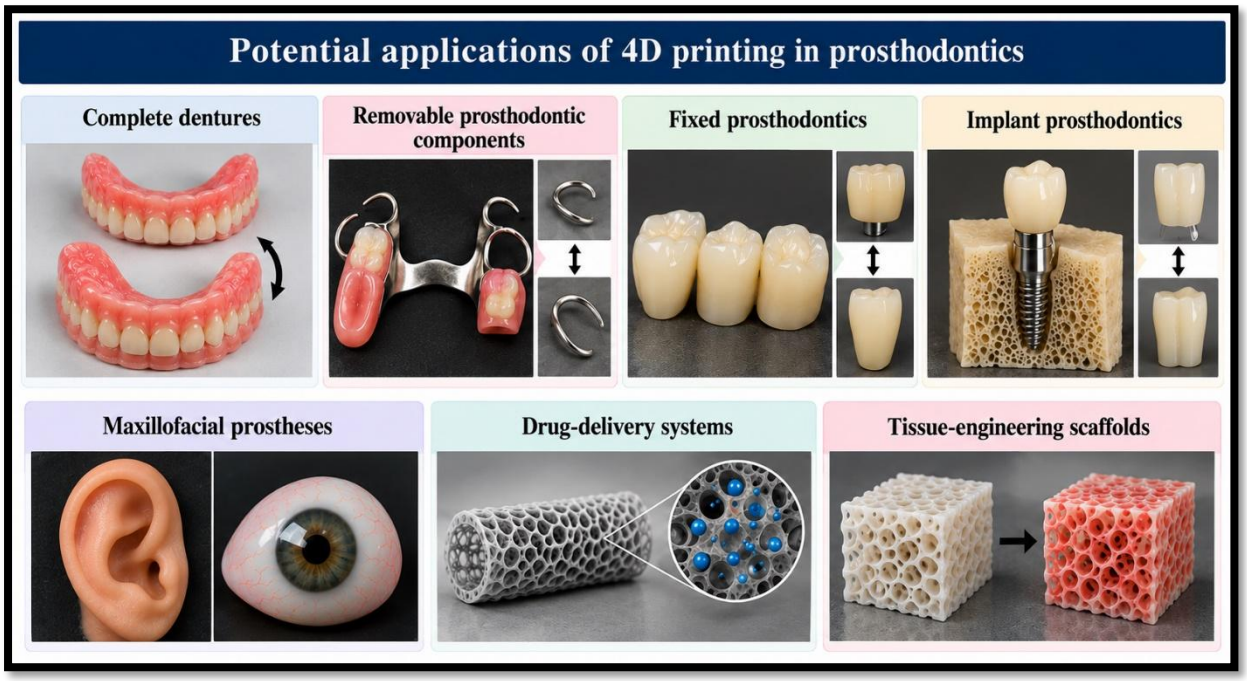

Figure 3: Potential Applications Of 4D Printing in Prosthodontics.

X. Conclusion

Four-dimensional printing extends additive manufacturing by incorporating programmed time-dependent changes in shape or function. Smart polymers, hydrogels, elastomers and responsive composites provide opportunities for adaptive dental structures, implant-related systems, maxillofacial prostheses, drug delivery and tissue engineering. [1–3]

However, most prosthodontic applications remain experimental or preclinical. The major requirements for translation are predictable stimulus control, mechanical durability, dimensional stability, biocompatibility, reproducible manufacturing and standardized testing. Future work should emphasize clinically meaningful adaptation rather than transformation for its own sake. If these requirements are addressed, 4D printing could extend digital prosthodontics beyond static patient-specific fabrication toward controlled temporal adaptation.

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