

Applications and Performance Enhancement of 4D-Printed Shape Memory Polymers in Biomedical Fields

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Abstract. Four-dimensional (4D) printing technology, combined with shape memory polymers (SMPs), permits controlled deformation of material constructs and thus finds applications across multiple disciplines. Due to favorable biocompatibility, this combined approach holds considerable promise for biomedical use. This review surveys recent advances in 4D-printed SMPs for biomedical purposes, focusing on applications such as tubular stents, bone tissue engineering scaffolds, drug delivery platforms, and biomimetic actuators. Current studies indicate that although 4D-printed SMPs generally exhibit acceptable biocompatibility for medical applications, their mechanical performance often falls short of clinical requirements. To overcome these limitations, the review categorizes enhancement strategies into two complementary directions: modifications of the 4D printing process and conventional material-level modifications of SMPs. It systematically summarizes prevailing approaches in both categories — for example, optimizing 4D printing parameters, alternating deposition of multilayer actuation materials, deliberate molecular-structure design, and physical blending — clarifies existing advances and limitations, and proposes a novel development pathway emphasizing “process–material” synergistic enhancement. These conclusions offer practical guidance for promoting the clinical translation of 4D-printed SMPs.

Keywords: 4D Printing; Shape Memory Polymers; Biomedical Applications; Performance Enhancement.

1. Introduction

4D printing adds a temporal dimension to conventional 3D printing, enabling materials to exhibit controllable deformation over time. And representing a major direction in the development of additive manufacturing. SMPs can undergo shape change in response to external stimuli—for example, thermal input, light, chemical triggers, or magnetic fields. And thus provide an appropriate material basis for 4D technologies [1].

The application of 4D-printed SMPs in biomedical contexts is rapidly expanding, and their capacity for programmable shape change and autonomous deployment enables innovative solutions such as minimally invasive delivery and site-specific deployment, which address limitations of conventional medical devices and facilitate personalized interventions. Nevertheless, performance constraints—especially in mechanical capacity, functional stability, and the speed or precision of actuation—remain significant. Motivating the development of targeted strategies for performance enhancement [2].

This review systematically surveys specific biomedical applications of 4D-printed SMPs, including vascular and other tubular stents. Including scaffolds for bone tissue engineering, drug delivery systems, and biomimetic actuators. It analyzes the principal performance limitations observed in these applications and summarizes corresponding improvement strategies at both the process and material levels, and finally the review proposes a process–material synergistic pathway for future development and highlights key challenges that must be addressed to promote clinical translation.

2. Biomedical Applications

Driven by rising demands for personalized medicine and ever-higher precision requirements for medical devices, 4D-printed SMPs present a promising strategy to overcome current technological bottlenecks in biomedicine. Their attributes — including self-healing, rapid and programmable shape transformation, and self-assembly — position them at the interface of materials science, medicine, biology, pharmaceuticals, and bionics, enabling collaborative solutions for precise, rapid, and patient-specific interventions. This review concentrates on applications of 4D-printed SMPs in tubular (conduit) scaffolds and bone tissue engineering [2].

2.1. 4D-Printed SMPs for Biomedical Tubular Stent Applications

Combining 4D printing with SMPs enables the manufacture of personalized vascular stents. They self-expand and recover to predetermined geometries when thermally activated at physiological temperature. Consequently, this capability simplifies minimally invasive deployment and improves geometric conformity to patient-specific vasculature; for instance, Gu et al. produced a shape-memory, spiral-structured branched vascular stent via DLP-based 4D printing. They used photopolymerizable ink (PU : HEMA : DMAEMA = 3 : 5 : 2). The device was designed for compact delivery (e.g., into the femoral artery). It achieved a tensile strength of 18.1 MPa, a shape-fixity of 97.3%, and a shape-recovery of 98.7%. These results indicate satisfactory mechanical performance and biocompatibility for clinical consideration [3].

Moreover, such stents may be tailored to individual anatomy and delivered via minimally invasive routes. Controlled deployment can be mediated by multi-stimulus triggers (for instance, physiological temperature, near-infrared irradiation, or magnetic fields). These capabilities improve procedural precision and lower the risk of vascular trauma. They also offer suitable biocompatibility and degradability for clinical applications. He et al. fabricated branched vascular stents of varied geometries by DLP-based 4D printing. They used multi-material strategies and structural diversity to realize personalized designs that respond reliably to temperature, NIR light, and magnetic fields [4].

Applications extend beyond vascular devices: 4D-printed SMPs have been used to fabricate tracheal stents and other conduit scaffolds with high biomimicry, and notably, KIM et al. used DLP to produce a bilayer, photocurable silk-fibroin hydrogel tracheal scaffold. This work represents the first reported use of photocurable silk fibroin in this context. Under physiological conditions, the scaffold's shape transformation can be finely regulated via intrinsic material parameters or external stimuli. Finite-element simulations predicted complex deformation behaviors. Experiments validated the creation of a tracheal tissue-mimetic construct, confirming the platform's capacity to generate biomimetic tissue scaffolds [5].

2.2. Applications of 4D-Printed SMPs in Bone Tissue Engineering

Poly(lactic acid) (PLA) represents a widely used thermoplastic bio-based SMP with favorable biocompatibility and appreciable mechanical strength; its properties can be modulated via molecular design and processing. For example, incorporation of hydroxyapatite (HAP) alters degradation kinetics and mechanical characteristics to better suit clinical timelines. Senatov et al. prepared PLA composites reinforced with 15 wt% HAP: composite filaments were produced by melt blending and used to print porous PLA/HAP scaffolds by FDM. Characterization showed mean pore diameters $\approx 700 \mu\text{m}$ and $\approx 30\%$ porosity, conducive to BMSC attachment and proliferation. Adding HAP increased T_g from 53°C (pure PLA) to 57°C and reduced thermal conductivity. Mechanically, the scaffolds reached a maximum recovery stress of 3.0 MPa and retained integrity (no delamination) after three compression–heating–recovery cycles; shape-fixity and shape-recovery values attained $\approx 98\%$. The authors proposed thermally triggered self-fitting behavior suitable for small-scale bone defect repair [6].

Subsequent work has combined enhanced mechanics and shape-memory behavior with bioactive cues to produce multifunctional scaffolds for bone repair. Yu et al. synthesized a shape-memory

polyurethane (SMPU) and fabricated porous scaffolds via a salt-leaching technique, controlling pore size by the salt particle dimensions. SEM demonstrated uniform pore distributions and porosities between 77.13% and 83.13%. Mechanical and biocompatibility assessments (compression testing, thermomechanical analysis, and cell culture with MG-63 osteosarcoma cells) indicated that larger pores correlated with higher recovery rates; MTT assays (1, 3, 5, 7 days) showed significantly increased cell proliferation relative to controls. The SMPU scaffolds, therefore, combine appropriate mechanics, tunable porosity, robust shape-memory behavior, and the ability to promote cellular proliferation[7].

2.3. Other Applications

Beyond stents and bone scaffolds, 4D-printed SMPs have found application in drug-delivery systems and biomimetic actuators. By exploiting structural design and stimulus responsiveness, these systems enable controlled motion, target-specific release profiles, and large-magnitude deformations, improving operational precision, payload capacity, and biocompatibility. Such capabilities support applications in targeted therapy, minimally invasive procedures, and soft robotics [8][9].

Hu et al. reported a millimeter-scale soft robot based on a thermally and magnetically dual-responsive nanocomposite hydrogel produced by 4D printing. By combining NdFeB magnetic particles with thermosensitive hydrogels, the team printed biomimetic geometries (e.g., shell- and starfish-like forms) capable of controlled locomotion and cargo transport under coordinated thermal and magnetic stimuli. Release kinetics were tunable by varying temperature and magnetic fields; drug-release and cell-culture assays confirmed acceptable biocompatibility. This study demonstrates a multimodal, dual-responsive soft biomimetic robot with programmable motion and release — a notable advance for targeted delivery, minimally invasive intervention, and microscale biomedical manipulation [8].

Pan et al. synthesized block copolymers of varied topologies that self-assemble into flower-like nanovesicles and serve as photocurable feedstocks for DLP-based 4D printing. The topology-dependent self-assembly produced actuators with multi-stimulus responsiveness; star-shaped (three-arm) copolymers conferred enhanced thermal stability and denser nanostructures, enabling printed actuators to reach bending angles up to $\sim 500^\circ$ under pH stimulation while maintaining strong shape-memory behavior and high load-bearing capacity. Via bilayer architectures and multi-material 4D printing, the authors fabricated an octopus-inspired biomimetic actuator exhibiting dual-responsive actuation (temperature and pH). This work links molecular topology to macroscopic actuation performance and provides a materials-and-design pathway for high-performance biomimetic actuators and intelligent microsystems [9].

3. Performance Limitations and Enhancements

Although 4D-printed SMPs show considerable promise in biomedical applications, their translation into routine clinical use remains constrained and requires further development, as summarized schematically in Figure 1. Present 4D fabrication techniques do not yet fully meet the precision demands of many biomedical devices. In addition, most available SMP formulations fall short of the mechanical-performance thresholds required for clinical deployment, and the range of reliable actuation mechanisms for shape-memory behavior remains limited [1] [10] [11].

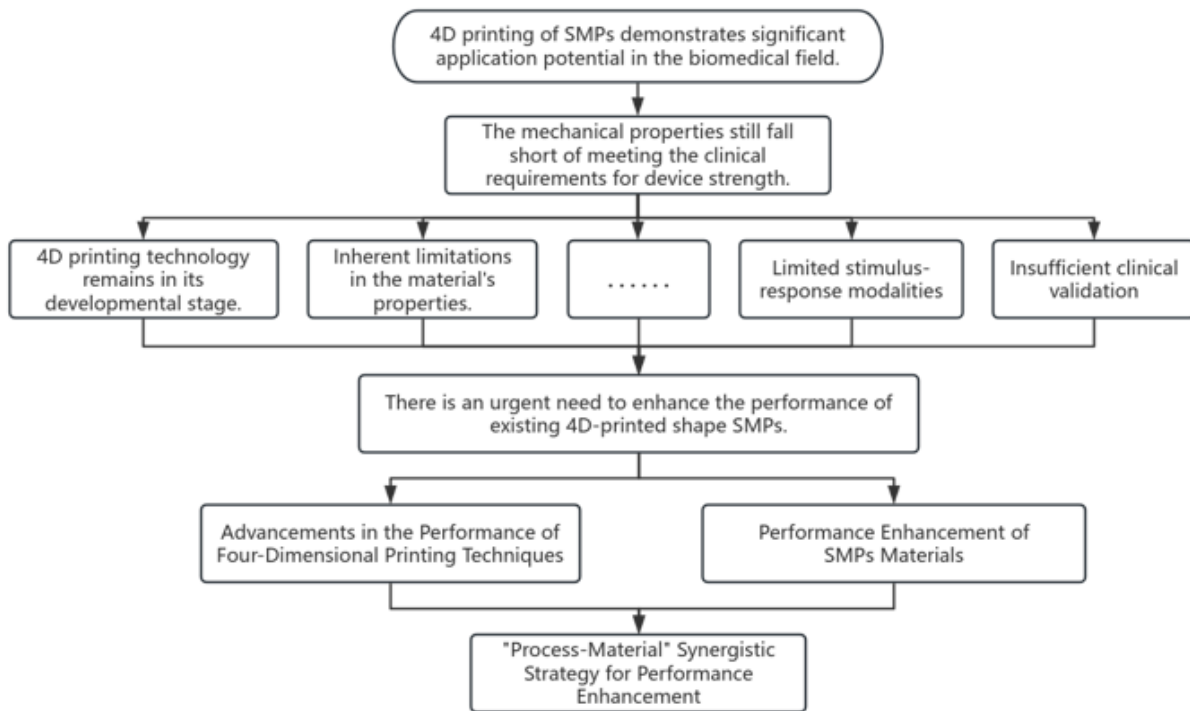


Fig 1. 4D-Printed SMPs: Performance Limitations & Optimization Diagram.

3.1. Process Modification Methods for 4D-Printed SMPs

Contemporary strategies to optimize 4D fabrication emphasize tailored process parameters, since fine-tuning printing settings can improve the performance of many SMP systems. Parallel advances demonstrate that introducing auxiliary printing constituents enables the production of multi-stimuli-responsive constructs, indicating that process-level modifications still hold substantial untapped potential for enhancing 4D outcomes [12] [13].

Zeng et al. implemented a multi-material co-extrusion 4D process to integrate continuous carbon fibers into a PLA-based SMP matrix, producing a shape-memory polymer composite (SMPC) that combines elevated mechanical strength with stimulus responsiveness. In their in-situ co-extrusion workflow, the fiber and polymer feeds were delivered separately into a high-temperature nozzle where the SMP melted (reported processing temperature 220 °C) and impregnated the fiber bundles before layer-by-layer solidification. Mechanical characterization revealed that load-bearing capacity depends strongly on fiber orientation (off-axis angle) and fiber content; appropriately increasing fiber fraction improved overall mechanical behavior. Shape-memory evaluation showed near-complete shape fixity ($\approx 100\%$) and a shape recovery rate of 96.3%, demonstrating robust programmability and recovery reliability and illustrating a feasible route to composites that couple structural load bearing with morphing function [14].

Other studies point to externally assisted, multilayer printing as a promising route to broaden stimulus modalities. For instance, WU et al. reported magnetic-field-assisted DLP-based 4D printing to produce multilayer composites with alternating conductive and magnetically responsive strata. These architectures permit activation either by Joule heating or by high-frequency magnetic induction; during fabrication, applied magnetic fields align magnetic particles unidirectionally, which markedly improves recovery performance. The alternating-layer approach enabled dual electrical/magnetic actuation with reported shape-fixity (R_f) and shape-recovery (R_r) values of approximately 96% and 97%, respectively—demonstrating enhanced actuation efficiency and controllability afforded by process-level innovations [13].

Namathoti et al. prepared FDM filaments by twin-screw extrusion of SMP blended with LDPE and PP at weight fractions of 5 %, 10 % and 15 %. These filaments were printed into 4D specimens, some of which received thermal annealing. While LDPE/PP blending lowered material cost, it initially

degraded certain mechanical and shape-memory attributes; thermal annealing substantially recovered performance and further improved strength, thermal stability, and shape recovery. Notably, the SMP/PP compositions annealed at 90 °C showed the best post-treatment performance. The study thus demonstrates a pragmatic, multi-path synergistic modification strategy for producing lower-cost, higher-performance SMPs suitable for 4D fabrication [15].

3.2. Conventional Modification Approaches for Shape Memory Polymers

Conventional strategies to modify SMPs include deliberate molecular-structure design, physical blending, addition of functional fillers, and extension or optimization of stimulus-response mechanisms (Figure 2). Of these, tuning response pathways and blend formulations is already widely practiced. Molecular tailoring—such as introducing dynamic covalent linkages (for example, boronic-ester or halogen bonds), engineering supramolecular interactions (hydrogen bonding, coordination bonds), or forming chemically cross-linked networks—has markedly improved mechanical metrics and enabled bidirectional or multi-step shape-memory behaviors. Physical blending affords control over glass transition temperature (T_g), crystallization kinetics, and phase morphology by combining SMPs with other polymers or monomers, thereby improving mechanical robustness while preserving high shape-fixity and recovery. Extending single thermal triggers toward multi-field actuation (light, magnetic fields, electrical stimuli, microwaves, etc.) is achieved via filler selection and structural design; examples include magnetothermal conversion using magnetic particles and photothermal–electrothermal synergistic triggering with carbon-based additives. Incorporation of functional fillers (e.g., Fe_3O_4 , Ag nanowires, CNTs, graphene) both raises mechanical and thermal conductivity and adds functionalities such as electrical conduction, electromagnetic shielding, and photothermal conversion—facilitating more intelligent, multi-responsive SMP systems. These modification pathways are complementary and, when combined, can evolve SMPs from single-function materials into high-performance, adaptive intelligent materials [11]

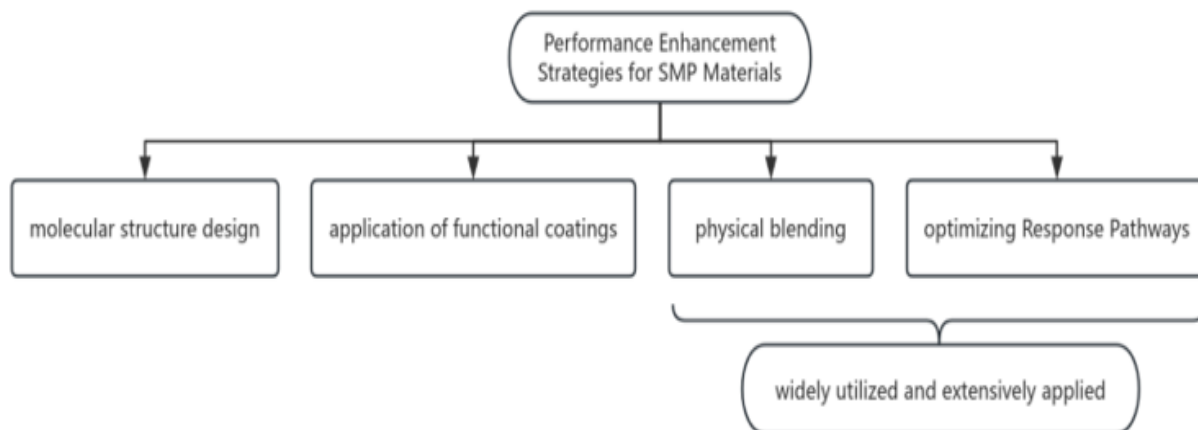


Fig 2. Performance Enhancement Diagram of SMPs Materials.

4. Innovations and Prospects

Integrating process-level innovations in 4D fabrication with conventional bulk modification strategies for SMPs constitutes a promising but relatively underexplored paradigm. Future work should emphasize the development of cooperative process–material modification strategies. This can yield cost-effective, high-performance, and high-precision 4D-printed SMPs with diverse functional capabilities. Such integrated approaches can accelerate clinical translation and expand personalized biomedical applications of 4D-printed SMP materials.

Performance-enhancement strategies for 4D fabrication should no longer rely solely on single-path modifications. Instead, they should evolve toward multidimensional, collaborative optimization that unites materials, processes, and application requirements. Only through such integration can interdisciplinary barriers be effectively overcome. For implantable devices, molecular-level design

must maintain robust shape-memory behavior. At the same time, it should emphasize biocompatibility and ensure an appropriate T_g , since these factors are equally essential. Crucially, when SMP design is coupled with 4D printing, the boundary between material formulation and processing dissolves, creating a dynamic interplay. This coupling allows coordinated control of both microstructure and printing parameters, thereby achieving a higher degree of precision. A full-chain, integrated design strategy—spanning from molecular architecture to macroscopic manufacturing and linking material properties with clinical constraints—provides a realistic and promising pathway. Such an approach fosters the clinical translation of 4D-printed SMPs while propelling the advancement of personalized biomedical technologies.

5. Conclusion

This review systematically surveys recent progress in applying 4D-printed SMPs to biomedical contexts. It pays particular attention to representative cases in tubular (vascular) stents and bone tissue engineering. It also evaluates prevailing performance limitations and the improvement strategies proposed to address them. Overall, 4D-printed SMPs show promise for use in vascular stents, bone-repair scaffolds, drug-delivery platforms, and biomimetic actuators. This promise is by virtue of programmable deformation, acceptable biocompatibility, and potential for minimally invasive deployment. Nonetheless, critical challenges persist. These include inadequate mechanical strength, limited printing accuracy, a narrow range of stimulus–response modalities, and insufficient clinical validation. To mitigate these constraints, current efforts follow two principal directions, and these directions operate in parallel. One direction seeks to refine 4D fabrication methods — for example, by optimizing printing parameters, enabling multi-material deposition, or integrating external-field-assisted molding — with the aim of improving printing accuracy and structural controllability. The complementary direction focuses on material-level modifications — such as molecular-structure engineering, physical blending, and addition of functional fillers — to enhance mechanical properties, bioactivity, and multi-stimuli responsiveness of SMPs. Importantly, improvements confined to either processing or material design alone are unlikely to deliver transformative change; accordingly, this review advocates a process–material synergistic pathway that coordinates printing parameters with deliberate microstructural design to achieve end-to-end control from molecular architecture to macroscopic device performance, thereby enhancing mechanics, functionality, and biocompatibility. Future work should emphasize interdisciplinary collaboration and close alignment with clinical requirements so as to enable comprehensive optimization across the material–process–application pipeline. By creating novel intelligent SMP formulations, improving printing methodologies, broadening multi-stimulus actuation strategies, and strengthening both *in vitro* and *in vivo* biological assessments, 4D-printed SMPs may progress from laboratory proof-of-concept toward clinical translation. Such advances are expected to unlock transformative applications in personalized medicine, minimally invasive surgical technologies, and regenerative tissue engineering, and thereby underpin the next generation of biomedical devices.

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