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AI-enhanced magnetically controlled 4D printing: Reshaping the future of medical robotics

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Abstract

As a frontier interdisciplinary breakthrough, magnetically controlled 4D printing integrates smart materials, additive manufacturing, and magnetic actuation, and is contributing considerably to healthcare practices. By introducing time as the fourth dimension, magnetic 4D-printed devices can dynamically transform their structure and function in response to physiological or external magnetic stimuli, enabling minimally invasive interventions with enhanced adaptability and precision. Integrating artificial intelligence (AI) into magnetically controlled 4D printing accelerates material discovery, optimizes design and manufacturing, and enables intelligent navigation and control in complex *in vivo* environments. Recent advances highlight promising applications in interventional therapy, targeted drug delivery, and tissue repair, yet challenges remain in achieving biocompatible multifunctional materials, scalable fabrication, and safe clinical translation. Looking ahead, synergistic integration of AI with multimodal actuation, digital twins, and biomimetic systems may unlock unprecedented opportunities for personalized, adaptive, and intelligent medical robots. This perspective outlines current progress, key challenges, and future directions of AI-enhanced magnetically controlled 4D printing, underscoring its transformative potential in redefining next-generation medical robotics.

Keywords: AI-enhanced 4D printing; Magnetic actuation; Medical robotics

1. Introduction

The advent of 4D printing represents a significant evolution and expansion of 3D printing technology.[1] By introducing time as the fourth dimension, 4D-printed robotics possess the capability to dynamically modify their shapes, functions, or properties in response to external stimuli, including temperature, light, pH, as well as electric and magnetic fields.[2] Magnetically 4D-printed magnetic robotics emerges as a revolutionary interdisciplinary technology at the intersection of smart materials, additive manufacturing, magnetic actuation, and machine learning.[3] Compared with other 4D printing approaches driven by stimuli such as heat, light, or humidity, magnetic 4D printing offers distinct advantages for medical applications. First, magnetic fields enable non-contact, remote, and tissue-penetrating control of device deformation, overcoming the limited penetration depth of light or thermal stimuli. Second, the strength and orientation of magnetic fields can be precisely adjusted, allowing rapid, reversible, and high-accuracy responses even in complex *in vivo* environments. Third, magnetic actuation avoids excessive local heating or chemical triggers, thereby ensuring superior safety and biocompatibility. These features make magnetic 4D printing particularly well suited for minimally invasive surgical tools, targeted drug delivery, and deep-tissue repair.[4] However, magnetic 4D printing still faces challenges in material optimization and functional integration, making the introduction of artificial intelligence (AI) essential to enhance efficiency in design, manufacturing, and control. In recent years, the rapidly advancing AI technology has demonstrated remarkable capabilities in significantly enhancing material functionalities, optimizing manufacturing processes, efficiently integrating medical imaging data, enabling path planning, and supporting dynamic control.[5] From our perspective, the true paradigm shift lies not merely in integrating AI into 4D printing workflows, but in rethinking the design–manufacture–control cycle as an intelligent, data-driven ecosystem. We posit that future magnetic 4D-printed medical robots will evolve from passive, material-based devices to adaptive, self-learning systems capable of closed-loop interaction with the human body. This viewpoint forms the conceptual foundation of this perspective. As shown in Figure 1, by enabling the development of AI, magnetically 4D-printed minimally invasive medical devices can adapt dynamically to complex physiological environments, reshaping the future of medical robotics.

In this perspective, our goal is not simply to review existing progress in magnetic 4D printing and medical microrobotics, but also to articulate a forward-looking framework for the intelligent, data-driven design–manufacture–control cycle. Rather than treating materials, fabrication, and actuation as isolated technological components, we advocate for their integration with AI to form closed-loop, adaptive, and clinically responsive robotic systems. This perspective thus aims to provide a conceptual roadmap that guides the field from device-centric innovation toward unified, intelligent, and clinically translational robotic ecosystems.

2. Materials, printing techniques, and core principles of magnetic 4D printing

2.1. Matrix materials and magnetic composites for 4D printing

Magnetically controlled 4D printing integrates magnetically responsive composites—consisting of matrix materials (*e.g.*, silicone, hydrogels, shape memory polymers) and magnetic fillers (superparamagnetic nanoparticles, soft/hard magnetic particles), with time as the fourth dimension. These materials undergo programmable shape transformations under magnetic stimulation, offering advantages like remote control, rapid response, and high biocompatibility, which align with biomedical demands for non-invasiveness and precision.[6] Ge *et al*. demonstrated one of the earliest practical implementations of 4D printing using shape-memory polymers, establishing the foundation for active materials capable of complex shape morphing under external stimuli.[7] More typical materials used in magnetically controlled 4D printing are summarized in Table 1.

2.2. Printing techniques and magnetization programming

Magnetic 4D printing currently relies on several additive manufacturing techniques, including stereolithography, fused deposition modeling, direct ink writing, and selective laser sintering. These processes utilize composites of magnetic particles with photosensitive resins, thermoplastic polymers, magnetic hydrogels, or powder-based systems to fabricate structures with different scales and properties. After printing, an external magnetic field is typically applied to orient the particles, thereby endowing the devices with programmable responsive behaviors.[8]

More specifically, the core principle can be summarized as follows: During printing or post-processing, magnetic particles are given specific orientations or magnetization patterns. When an external magnetic field is applied, the magnetic components inside the material generate torques and stresses that drive the entire structure to deform according to the pre-programmed design. Soft magnetic particles can flexibly respond to changing fields to achieve gripping or locomotion, whereas hard magnetic particles maintain stable magnetization, enabling complex yet predictable deformations even under uniform fields. Through time-sequenced magnetic control, devices manifest dynamic, controllable, and personalized functions along the "fourth dimension."[9] Building on these unique features, the feasibility of applying magnetic 4D printing

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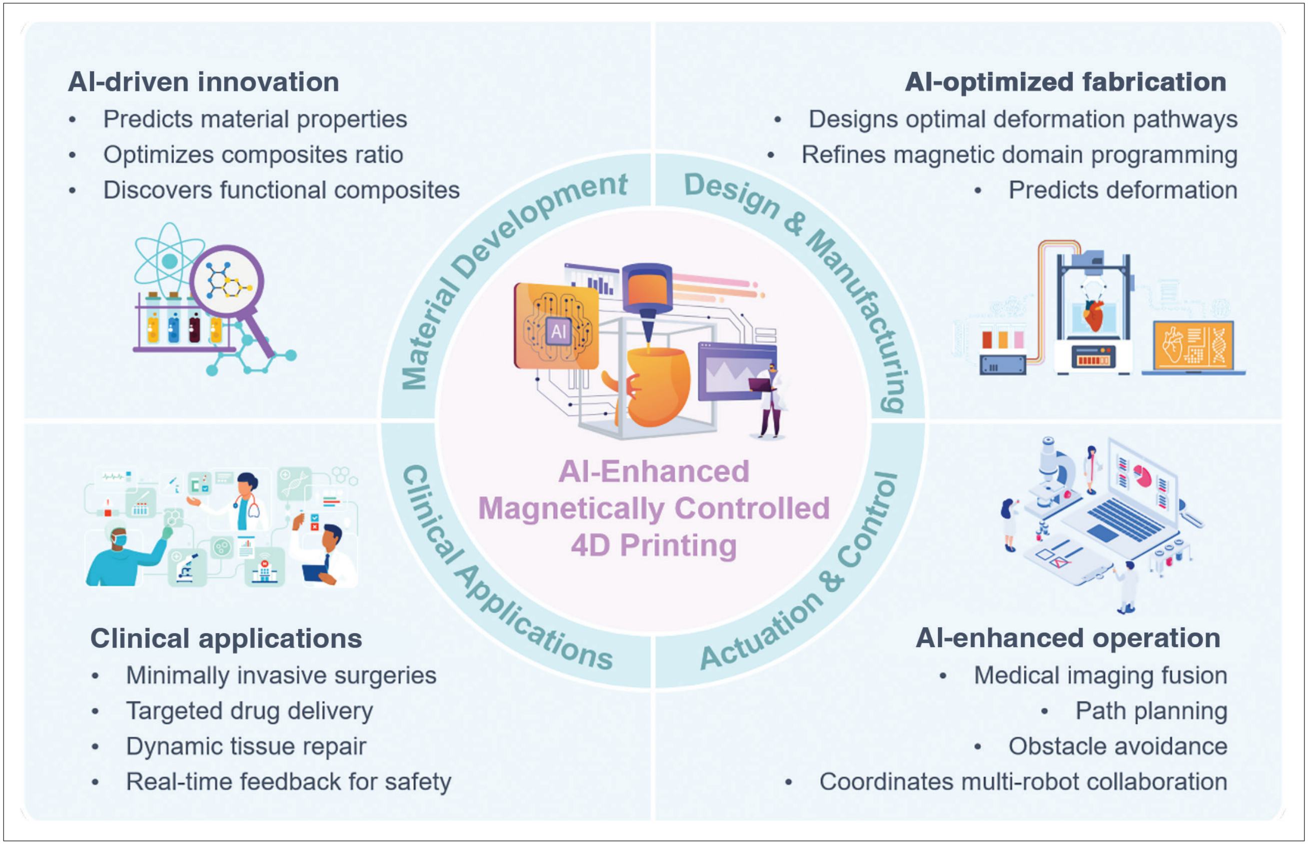

Figure 1. Future prospects of AI-enhanced magnetically controlled 4D printing in medical robotics. Schematic created with BioRender. Yu, L. (2025) https://BioRender.com/j5t9ayd (Agreement No. PQ28YQY00U).

in clinical settings becomes increasingly clear, naturally leading to its translational potential in medical robotics.

2.3. Function-driven material design guidelines for biomedical translation

Although magnetically responsive materials have shown impressive shape-morphing and actuation, translating them into biomedical use calls for function-driven design rather than material-driven selection. Different clinical scenarios impose distinct targets for mechanical compliance, magnetic actuation efficiency, *in vivo* stability, and biodegradation kinetics: short-term therapeutic implants should match soft-tissue elasticity—approximately 10 to several tens of kilopascals to minimize inflammatory mechanical mismatch[10]—and undergo controlled biodegradation within about 2–16 weeks to align with wound healing[11,12]; tissue-regeneration and load-transferring scaffolds require higher stiffness, on the order of 0.5–20 GPa to sustain structural support, with degradation profiles tuned to the indication, and many such applications benefit from moderate timelines of roughly 3–6 months to track tissue remodeling[13]; for long-term or permanent interventional devices intended to function for years to decades, the prevailing strategy is to eliminate biodegradation entirely or reduce it to a rate that is effectively negligible within the patient's lifetime. Together, these criteria establish a material–clinical function matching framework that guides the selection and engineering of magnetic 4D-printing materials according to therapeutic goals.

3. Translational advances of magnetic 4D printing in medical robotics for clinical therapy

Magnetic 4D printing's clinical potential spans critical areas. In interventional therapy, 4D-printed devices such as bioabsorbable left atrial appendage occluders and tracheal stents overcome limitations of traditional rigid instruments by adapting to anatomical structures via magnetic actuation, reducing tissue damage and enabling controlled degradation.[22] Targeted drug delivery systems, including magnetically guided soft robots and hydrogel-based carriers, navigate complex luminal environments (*e.g.*, gastrointestinal tract, blood vessels) to release therapeutics precisely at lesion sites, minimizing systemic

Table 1. Typical materials for magnetically controlled 4D printing

	Materials	Magnetic properties	Actuation mechanisms	Mechanical properties/Printability	Biocompatibility/biodegradability	Examples	Ref.
Matrix	Shape memory polymer	Non-magnetic	Light, water, magnetism, electricity, and heat-induced actuation	Good elasticity	Biodegradable	Polyolefin elastomers	14,15
	Silicone	Non-magnetic	Magnetically induced passive deformation	Good elasticity	Non-degradable but compatible	SE1700, Ecoflex	16
	Hydrogel	Non-magnetic	Magnetically induced passive deformation	Low mechanical strength	Highly biodegradable	PEG, PEGDA	17
	Liquid crystal elastomer	Non-magnetic	Magnetically induced passive deformation	Good elasticity	Customizable degradation properties	RM82	18
Magnetic fillers	Hard magnetic particle	High remanence, high coercivity	Permanent magnetic domains suitable for complex programmed magnetic fields	Easy to sedimentation	Toxic	NdFeB	19
	Soft magnetic particles	High remanence, low coercivity	No pre-programmed magnetic domain, complex trajectories typically require time-varying/gradient fields	Better dispersion	Biodegradable	Fe, Ni	20
	Superparamagnetic nanoparticles	No remanence, no coercivity	No residual magnetization (reduces aggregation after actuation), but needs strong gradients or higher volume fraction for noticeable forces	Easily for mix in matrix precursors, and suitable for printing	Biodegradable	SPIOs	21

Abbreviations: PEG, poly(ethylene glycol); PEGDA, poly(ethylene glycol) diacrylate; SPIOs, superparamagnetic iron oxide nanoparticles.

side effects.[23] For tissue repair, smart scaffolds and patches achieve on-demand adhesion, controlled release of growth factors, and biodegradation, accelerating wound healing and regeneration.[24] However, to enable these functions to operate efficiently in complex *in vivo* environments, more intelligent design and control strategies are required—this is precisely where AI emerges as a pivotal enabler.

4. AI as a pivotal enabler across the lifecycle of magnetic 4D-printed medical robotics

In magnetically controlled 4D printing, the dominant AI paradigms are machine-learning and deep-learning frameworks. Supervised regression models—random forests and support vector machines foremost among them—map composition, filler dispersion, and field strength to macroscopic deformation with prediction accuracies consistently exceeding 90%, outperforming traditional finite element analyses by orders of magnitude in computational speed. For 3D morphing patterns that obey Maxwell–Cauchy constraints, convolutional neural networks and physics-informed neural networks encode spatial–temporal features while explicitly embedding conservation laws, thereby guaranteeing generalizability beyond the training manifold. Reinforcement learning agents and model predictive control (MPC) schemes close the loop *in vivo*: a reinforcement learning policy learns optimal actuation sequences through interaction with a hemodynamic simulator, and the MPC layer refines magnetic field vectors in real time using stereoscopic imaging feedback, ensuring robust path-planning and attitude regulation despite physiological variability. Collectively, these algorithms endow the entire magnetically controlled 4D-printing pipeline—from inverse design of particulate composites to closed-loop navigation in deep tissue—with quantifiable predictability and deterministic controllability.[25,26]

The integration of AI with magnetic 4D printing fundamentally lies in translating "desired functions" into "actionable designs and controls." While magnetic 4D printing uses external fields to deform flexible composites embedded with magnetic particles, AI enables rapid prediction and inverse identification of the optimal structures and field inputs needed to achieve a given function. In this way, AI acts as a "bridge," translating the desired clinical function into specific printing parameters and magnetic control strategies, and continuously refining them with feedback during operation, thereby enabling more intelligent and controllable medical applications.[27] Building on this principle, the role of AI extends far beyond conceptual modeling, permeating material development, structural design, manufacturing, and real-time navigation and control throughout the entire lifecycle of magnetic

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4D-printed medical robotics. In material development, machine learning and deep learning algorithms predict material properties (magnetic responsiveness, mechanical strength, biocompatibility) from compositional data, accelerating the discovery of multifunctional composites. For example, AI models optimize magnetic filler concentration and surface functionalization to balance performance and safety.[28] In design and manufacturing, generative AI autonomously creates robotic architectures with optimal deformation pathways, while reinforcement learning refines magnetic domain programming, ensuring structures bend, twist, or contract as intended under magnetic fields. AI also enhances deformation prediction, replacing cumbersome physical simulations with efficient data-driven models. Intelligent control systems, powered by AI, address critical challenges in *in vivo* navigation. By fusing medical imaging (MRI, CT, ultrasound) with real-time feedback, AI enables precise path planning, obstacle avoidance, and adaptive motion control in dynamic environments like blood flow.[29] Reinforcement learning and MPC algorithms allow robots to learn and adapt to physiological variations, ensuring stable performance in unpredictable conditions.[30] Moreover, advanced learning strategies support swarm intelligence, allowing multiple magnetic microrobots to coordinate complex tasks *in vivo*, such as collective transport or parallel drug delivery.[31] By integrating patient-specific imaging and physiological data into the design pipeline of magnetic 4D printing, AI enables the creation of digital twins that simulate how magnetically actuated devices deform and navigate *in vivo*. This allows personalized device optimization and preoperative rehearsal, while also supporting real-time surgeon–robot interaction through adaptive trajectory correction during minimally invasive procedures.[4,32] When combined with magnetically actuated deformation models, AI-driven predictive algorithms can evaluate therapeutic responses—such as drug release profiles or tissue remodeling—and dynamically tune magnetic field sequences. In this way, the printed devices operate under a closed-loop control framework that enhances clinical outcomes.[29] In the translational pathway, AI enhances the safety of magnetic 4D-printed systems by continuously monitoring their actuation parameters and simulating worst-case scenarios, such as overheating or excessive field exposure. This predictive capability supports regulatory approval and ensures reliable and ethical deployment of these devices in clinical settings.[5]

Although the integration of AI has significantly expanded the capabilities of magnetic 4D printing, numerous challenges remain in material development, manufacturing processes, and clinical applications. These challenges not only determine whether the technology can be successfully translated but also highlight the pressing issues that future research and cross-disciplinary collaboration must address.

5. Discussion and conclusion

Despite progress, key challenges remain in magnetic 4D printing. Material development faces hurdles in balancing magnetic responsiveness, mechanical robustness, and biocompatibility, particularly for long-term *in vivo* applications, and high-precision magnetic domain programming and scalable manufacturing of micro/nano-scale structures demand advances in printing hardware and process control. In clinical translation, issues like real-time deep-tissue imaging, force feedback, and regulatory approval for “actively intelligent” devices require interdisciplinary collaboration. Ethical concerns, including data privacy for AI-driven systems and liability for autonomous decisions, also need addressing.

Future directions should focus on multimodal integration, combining magnetic actuation with other stimuli (light, heat) for enhanced functionality; personalized medicine, leveraging patient-specific data to design tailored devices via AI digital twins; and biomimetic systems that integrate 4D-printed scaffolds with live cells for organ repair. Miniaturization toward micro/nano-robots will enable cellular-level interventions, while AI-driven closed-loop systems (design-simulation-manufacturing-feedback) will accelerate clinical translation.[33–35]

While recent studies have demonstrated proof-of-concept devices, we posit that the field is approaching a critical bottleneck. The majority of current works remain proof-of-concept demonstrations in *ex vivo* or small-animal models, with limited scalability, reproducibility, or clinical relevance. Three fundamental gaps persist:

(i) *Material gap:* There is no standardized biomaterial platform that simultaneously satisfies magnetic responsiveness, mechanical resilience, biodegradability, and cytocompatibility. Most studies optimize for one property at the expense of others, leading to fragile trade-offs that hinder translational potential.

(ii) *AI gap:* Although widely promoted, AI remains underutilized in achieving closed-loop feedback and control. Most AI models are trained offline on synthetic or idealized datasets and therefore fail to generalize to intra-patient variability, including bleeding, peristalsis, and inflammation. We lack real-time, adaptive AI systems that can learn *in vivo*, not just simulate *ex vivo*. Furthermore, AI systems face challenges of data dependency and limited generalizability, as large, high-quality training datasets are still scarce in biomedical magnetic 4D printing, restricting the ability of these models to perform reliably in complex *in vivo* environments.[25]

To move beyond the current AI gap, we emphasize that progress requires not only more powerful model architectures, but more importantly, large-scale, standardized, and shareable datasets that reflect real spatiotemporal complexity in both *in vitro* and *in vivo* environments. To this end, we propose two concrete and field-scalable strategies:

- *Data reporting protocol for magnetic 4D printing experiments:* We recommend establishing a unified data reporting framework that standardizes how magnetic 4D printing studies document experimental conditions and outcomes. Key elements include: (a) Magnetic field inputs: strength, gradient, waveform, temporal sequencing. (b) Magnetization programming: magnetic domain orientation patterns, encoding method, spatial resolution. (c) Quantitative motion outputs: deformation amplitude, actuation efficiency, kinematic trajectories, and dynamic response profiles in both *in vitro* and *in vivo* environments. Standardizing these parameters will enable reproducible benchmarking across laboratories, reduce irreproducibility artifacts, and facilitate data-driven comparison of magnetic actuation strategies.
- *Open-source data repository for medical microrobotics and 4D bioprinting:* We advocate for the establishment of a shared, continuously expanding data repository to house raw and processed kinematic datasets, magnetic field control sequences, imaging data from studies, and annotated clinical translational case prototypes. Such a repository would support collaborative model training, foster transparent comparison of AI control systems, and accelerate the development of generalizable, adaptive navigation and actuation intelligence for real-world biomedical applications.

Taken together, these initiatives outline a practical roadmap toward overcoming the AI Gap, transforming AI from offline, static prediction tools into clinically robust, closed-loop intelligent control systems capable of operating reliably in patient-specific physiological environments.

(iii) *Clinical gap:* Regulatory pathways for actively intelligent implants remain largely undefined. Unlike passive implants, AI-enhanced magnetic robots exhibit dynamic, adaptive, and partially autonomous behaviors, often with decision-making processes that are not fully transparent. Although the regulatory landscape for intelligent and adaptive medical devices is still evolving, several frameworks offer useful precedents. The U.S. Food and Drug Administration has introduced the Software as a Medical Device framework and the Good Machine Learning Practice principles, emphasizing transparency, traceability, and post-market monitoring of AI-enabled systems. Similarly, the European Medicines Agency released its Guideline on Artificial Intelligence and Machine Learning in the Development of Human Medicines (2023), which outlines requirements for data governance, algorithm validation, and clinical performance evaluation under the Medical Device Regulation (MDR 2017/745). For biohybrid or degradable materials, international standards such as ISO 10993 (biocompatibility) and ISO/TR 20416 (post-market surveillance) remain applicable. These developments highlight persistent ethical and legal uncertainties surrounding accountability, data protection, and patient safety. Major barriers to clinical translation and regulatory approval remain, as AI-driven magnetic systems have yet to achieve full compliance with established clinical standards of safety, robustness, and ethical governance. Addressing issues such as excessive magnetic exposure, real-time control reliability, and data privacy will require coordinated efforts across materials science, robotics, clinical medicine, and bioethics.[4] Bridging these three gaps—material, AI, and clinical—will be essential for transforming magnetic 4D printing from a proof-of-concept technology into a clinically deployable platform.

In conclusion, AI-enhanced magnetically controlled 4D printing holds transformative potential for medical robotics, enabling safer, more precise, and personalized therapies. By overcoming current technical and regulatory barriers through cross-disciplinary innovation, magnetically controlled 4D printing is poised to redefine minimally invasive interventions, drug delivery, and tissue engineering, ultimately improving patient outcomes.

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Conflict of interest

The authors declare that they have no competing interests.

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Visualization: Qi Wang, Jinrun Liu, and Juan Liu
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Ethics approval and consent to participate

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Consent for publication

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