Advances in magnetically controlled medical robots

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In the 1950s, Nobel laureate Richard Feynman envisioned the concept of "swallowing a surgeon," proposing that microscopic robots could be ingested or implanted into the human body to access and treat lesions unreachable by conventional surgical techniques. With the rapid advancement of micro/nanofabrication, materials science, and robotics, miniaturized medical robots capable of navigating through narrow anatomical lumens to perform diagnostics, targeted drug delivery, and minimally invasive therapies have gradually entered the research spotlight. Owing to the inherent size and power constraints of these robots, their actuation strategies currently rely mainly on pneumatic, hydraulic, ultrasonic, optical, electrical, and magnetic driving mechanisms.[1] Among these, magnetic actuation has emerged as one of the most promising approaches, offering excellent tissue penetration, high biocompatibility, and precise, wireless controllability.[2-3]

In recent years, magnetically controlled medical robots have experienced remarkable progress, spanning centimeter-scale capsule robots, millimeter-scale continuum robots, and micrometer-scale microrobots. These devices demonstrate unique advantages in diverse medical domains, including cardiovascular interventions, gastrointestinal diagnostics and therapy, pulmonary biopsy and ablation, and urological procedures (Figure 1A). However, the successful clinical translation of magnetic robots still faces several technological hurdles, such as actuation platform design, control algorithms, material biocompatibility, and functional integration.

INNOVATION AND POTENTIAL MEDICAL APPLICATIONS

Design strategies and potential biomedical applications for magnetically controlled robots

Based on their structural configuration, magnetically controlled medical robots are broadly categorized into tethered and untethered systems. Tethered robots, typically continuum structures with magnetic materials embedded at the tip with diameters ranging from millimeters to micrometers, are introduced through natural orifices to perform diagnostic or therapeutic tasks, such as in magnetically steered endoscopes and soft continuum manipulators. Their steering is controlled by external magnetic fields acting on the magnetic tip, while propulsion is provided by manual manipulation or external actuators. In contrast, untethered robots rely entirely on external magnetic fields for both power and control. Ranging from centimeter-scale capsules to micrometer-scale microrobots, they can access anatomical regions unreachable by tethered systems. Representative examples include capsule endoscopes and magnetically actuated ferrofluid-based microrobots. Under external magnetic fields, these robots achieve locomotion through rolling, swinging, or rotating, while collective swarm control strategies enable coordinated multi-robot operations.[4]

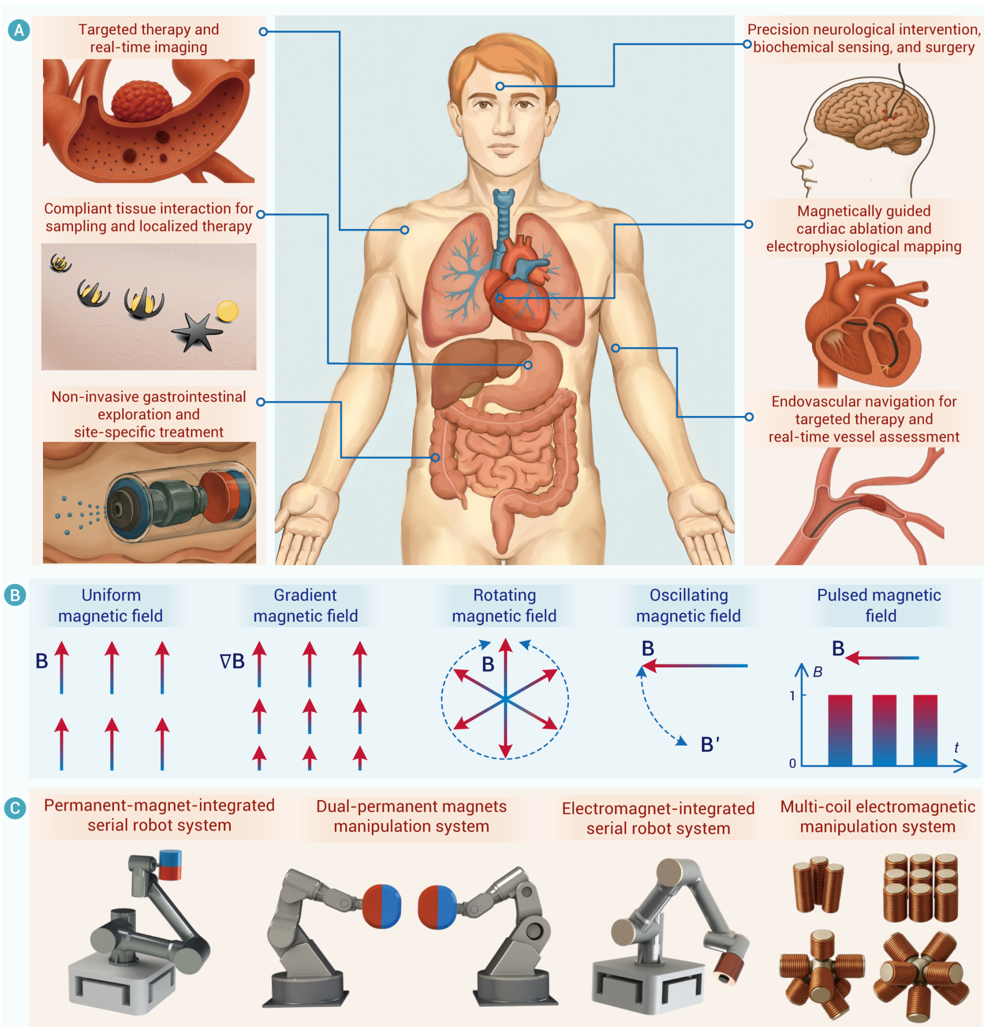

Figure 1. Design, control, and applications of magnetically controlled medical robots (A) Key application domains. (B) Types of control magnetic fields. (C) Magnetic control platforms.

Magnetically controlled continuum robots integrate manual or mechanical propulsion with active magnetic steering to overcome the hydrodynamic constraints of intravascular environments. This hybrid configuration provides the high mobility and stability necessary to navigate complex vascular networks against blood flow. Structurally, active tip control is typically achieved through two approaches: (1) Passive magnetic tips, employing PDMS integrated with composite permanent magnets or ferromagnetic particle-dispersed polymers; and (2) Active micro-coils, where magnetization is dynamically altered by modulating current phase, amplitude, and frequency. Both designs interact with external driving fields to enable high-precision navigation. Clinically, the superior steering capability of these robots facilitates access to regions beyond the reach of conventional tools. In vascular surgery, they enable stent delivery and the treatment of occlusive diseases such as cerebral aneurysms and ischemic stroke. Beyond endovascular applications, they improve retrograde intrarenal surgery by replacing traditional catheter guides and offer minimally invasive solutions for vitreoretinal disorders (e.g., retinal detachment). Furthermore, when integrated with electrochemical sensors, these robots show great potential for multi-site biochemical sensing within the brain.

Magnetically controlled capsule robots are designed to actively navigate fluid environments and flexible lumens within the human body for diagnosis and treatment. For gastrointestinal (GI) locomotion, embedding permanent magnets enables the robot to generate helical motion under rotating external magnetic fields. This propulsion mechanism leverages fluid reaction forces and provides self-centering capabilities, thereby minimizing tissue contact and enhancing obstacle traversal. Locomotion efficiency is further optimized through spiral or streamlined shell designs. Beyond rigid structures, bio-inspired soft robots utilizing silicone or hydrogel substrates exploit magnetic compliance to achieve multimodal locomotion, such as swimming, crawling, rolling, and jumping. In therapeutic applications, these robots are particularly promising for targeted drug delivery. By navigating to pathological sites under magnetic guidance, they overcome the limitations of oral medications—such as gastric degradation—and avoid the discomfort of invasive procedures. Various release mechanisms have been developed: one utilizes magnetic moment-induced folding to expel liquid drugs, while another employ anchoring leg deployed via rotation to counteract peristalsis. Furthermore, advanced designs integrate functionalities for negative pressure-based fluid sampling and optical detection.

Magnetically controlled microrobots are typically fabricated by incorporating magnetic nanoparticles and can be effectively propelled by various external magnetic fields, enabling flexible locomotion and complex swarm reconfiguration. By leveraging external magnetic fields to generate torque, these robots achieve rolling, tumbling, and oscillating motions, and can accomplish long-distance navigation under ultrasound guidance. Magnetically functionalized chitosan micro-scaffold robots, with optimized shape and pore properties, exhibit good biocompatibility and biodegradability. They utilize bio-material-based magnetic particles to provide magnetic actuation and enhance cell adhesion, and have been tested in vivo for liver cancer treatment and knee cartilage regeneration. Furthermore, programmable microrobots based on single-domain nanomagnet arrays represent another advanced design. By applying specific magnetic field sequences to nanomagnets with tailored switching fields, multiple shape-transformation instructions can be encoded into the microrobot. Nanoparticle swarms, which mimic the collective motion of wild herring schools or the rolling locomotion of leukocytes, can maintain stability and resist the impact of high-speed fluid flows in the bloodstream under external magnetic guidance. They can anchor at the target site and disperse upon withdrawal of the magnetic field, significantly reducing the risk of thrombosis and demonstrating pronounced targeting efficacy in treating subcutaneous tumors.

Magnetic actuation platforms

Magnetic fields for robot manipulation can be classified as uniform, gradient, rotating, oscillating, and pulsed fields, each producing distinct mechanical effects. Uniform fields generate magnetic torque to control orientation; gradient fields provide translational forces; rotating fields induce synchronous rotation of magnetic components; oscillating fields produce periodic swing-like motions; and pulsed fields enable intermittent actuation. Rotating, oscillating, and pulsed fields are often combined to achieve complex locomotion modes such as helical swimming or peristaltic motion (Figure 1B). Magnetic platforms are generally divided into permanent-magnet-based and electromagnet-based systems. Permanent-magnet systems achieve manipulation by mechanically rotating or translating permanent magnets, offering high field strengths and large working spaces. However, their field distributions are inhomogeneous, and magnetic force and torque cannot be independently adjusted. Electromagnetic platforms, on the other hand, use multiple orthogonally arranged coils to generate composite fields whose magnitude, direction, and frequency can be precisely modulated by controlling coil currents.[5] Typical configurations include Helmholtz coils for uniform fields, Maxwell coils for constant gradients, and saddle coils for field switching. A combination of three orthogonal Helmholtz coil pairs can produce a uniform field with arbitrary rotation, enabling precise torque-based robot manipulation (Figure 1C).

KEY CHALLENGES AND FUTURE DIRECTIONS

Magnetically controlled medical robots are currently transitioning from laboratory exploration to clinical translation. However, critical barriers remain regarding manipulation precision, functional integration, and biocompatibility. Specifically, magnetically controlled continuum robots lack force sensing and real-time feedback, necessitating the development of magneto-actuated closed-loop strategies that integrate multimodal imaging (e.g., ultrasound, MRI) and micro-force sensors. Capsule robots face hurdles in balancing miniaturization with navigation accuracy, which requires pursuing modular designs for efficient diagnostic-therapeutic integration and high-resolution magnetic positioning systems. Furthermore, microrobots are challenged by cross-scale locomotion and swarm coordination; future advancements must focus on biodegradable materials and AI-driven adaptive algorithms to enable precise control in complex environments. Addressing these technological bottlenecks is essential for meeting strict clinical standards and regulatory requirements.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.