



A magnetic slime robot for minimally invasive kidney stone retrieval: design, characterization, and in vitro validation

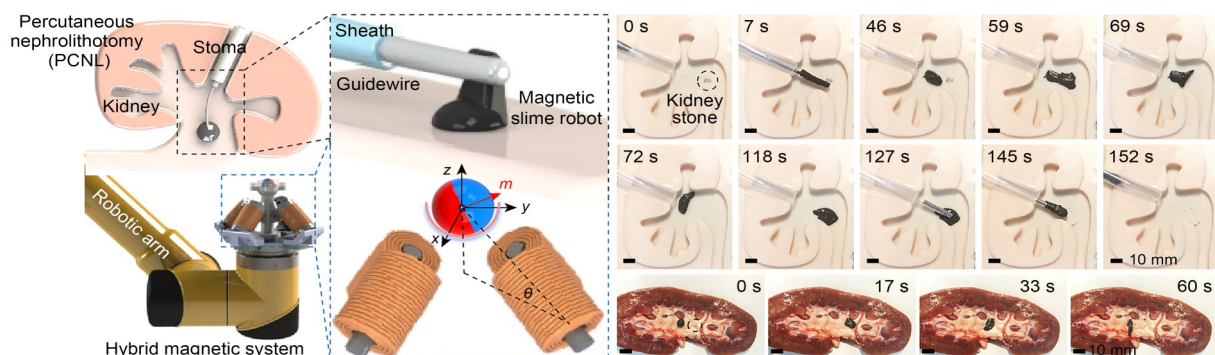
Hao Zhang¹ · Feihao Wang¹ · Jiashuo Zhang¹ · Hui Xie¹

Received: 6 March 2026 / Accepted: 19 May 2026
© Zhejiang University Press 2026

Abstract

The retention of residual kidney stone fragments following surgical removal, which is a primary cause of recurrence, remains a significant clinical challenge in urology. Inspired by the adaptability of natural mucilage and the efficiency of magnetic actuation, we propose a magnetic slime robot (MSR) specifically designed for percutaneous nephrolithotomy (PCNL), featuring a dedicated hybrid magnetic actuation system and a complete clinical workflow to address targeted residual fragment clearance. The MSR is fabricated from a polyvinyl alcohol–borax matrix embedded with NdFeB particles, and exhibits non-Newtonian fluidic behavior, self-healing properties, and controllable adhesion. Unlike systems relying solely on the movement of permanent magnets or static coil arrays, the custom hybrid system—which integrates electromagnetic coils with a spherical permanent magnet mounted on a robotic arm—generates programmable gradient, rotating, and oscillating fields, enabling robust multimodal deformation and locomotion for the highly viscous MSR in confined spaces. In vitro experiments in silicone and porcine kidney models demonstrate the MSR's ability to encapsulate stones up to 8 mm in diameter, navigate complex terrains with a tracking error of ≤ 1.3 mm, and clear stones within 3 min. This work establishes the MSR as a promising solution for improving postoperative stone clearance in PCNL.

Graphical abstract



Keywords Magnetic slime robot (MSR) · Non-Newtonian fluid · Bio-inspired design · Kidney stone retrieval · Percutaneous nephrolithotomy (PCNL)

Hao Zhang and Feihao Wang have contributed equally to this work.

✉ Hui Xie
xiehui@hit.edu.cn

Hao Zhang
haoz@hit.edu.cn

¹ State Key Laboratory of Robotics and Systems, Harbin Institute of Technology, Harbin 150080, China

1 Introduction

Kidney stones, which are crystalline aggregates formed due to the supersaturation of minerals and salts in urine, pose a significant global health burden, affecting approximately 12% of the population worldwide [1]. Current primary treatments such as shockwave lithotripsy, ureteroscopic lithotripsy, and percutaneous nephrolithotomy (PCNL) aim to fragment and remove large stones while relying on small fragments to pass naturally [2]. However, a major limitation of such approaches is the incomplete retrieval of residual fragments, which can serve as *nidi* for recurrence and lead to complications such as urinary tract infections [3]. Thus, to enhance postoperative clearance of residual fragments, innovative techniques have been developed, including ultrasonic propulsion [4], bioadhesive systems [5, 6], magnetic extraction [7], and aspiration systems [8]. Nonetheless, these techniques are often constrained by insufficient magnetic coupling for fragment retrieval and the inability of suction systems to maintain patency, underscoring the need for novel approaches.

Miniature soft-bodied robots have garnered significant research interest due to their compliant and deformable nature, which enables non-invasive access to confined spaces [9]. This offers promising solutions for minimally invasive surgery, micromanipulation, and targeted drug delivery [10–13]. Numerous actuation methods, such as thermal [14], optical [15], electrical [16], and magnetic [17, 18] drives, have been explored for miniature robots. Among them, magnetic actuation is particularly promising for biomedical applications, owing to its strong tissue penetration, rapid response, high programmability, and excellent biocompatibility [19–21]. For scenarios such as kidney stone retrieval and cargo transport, fluid-based miniature robots, including liquid metal, ferrofluid, and non-Newtonian fluid droplets, demonstrate remarkable potential due to their inherent fluidity, adaptability, and reconfigurability [22–24]. Unfortunately, these platforms possess inherent limitations. For instance, liquid metal robots often require an auxiliary thermal field to induce a phase change for enhanced load-bearing capacity [25, 26], while ferrofluid robots typically necessitate specific immiscible operating media (e.g., oil-based ferrofluids in aqueous environments) to maintain structural integrity; these factors significantly constrain operational adaptability [24, 27–29].

In contrast, magnetic slime robots (MSRs), which have emerged as a novel class of non-Newtonian fluid robots, combine the large-deformation capability of fluids with the environmental adaptability of elastomers [30]. They exhibit excellent shape-morphing, self-healing, and adhesion properties, making them suitable for grasping, transporting, and releasing cargo in complex environments [17, 30, 31]. But while pioneering studies have demonstrated the fundamental material properties and basic locomotion of MSRs [32], targeted biomedical applications of MSRs involving specialized

actuation and clinical workflows remain unexplored. In addition, the manipulation of these high-viscosity slime robots, which typically relies on the motion of permanent magnets to generate sufficient magnetic force [33, 34], often involves complex control strategies. At the same time, the rapid spatial decay of the magnetic field gradient can limit actuation efficiency across different working scenarios [30, 31]. Therefore, developing a magnetic actuation system that can generate diverse magnetic field modalities is crucial for simplifying the control and enhancing the manipulation performance and environmental adaptability of slime robots.

To address the clinical challenge of incomplete residual kidney stone fragment clearance following procedures like PCNL, which can lead to stone recurrence and infections, we propose an MSR for targeted postoperative retrieval. The MSR is fabricated from a polyvinyl alcohol (PVA)–borax cross-linked matrix embedded with NdFeB particles, and exhibits non-Newtonian fluidic behavior, self-healing, and controllable adhesion. To achieve the multimodal deformation and locomotion required for complex surgical environments, a dedicated hybrid magnetic actuation system is developed, integrating electromagnetic coils with a spherical permanent magnet mounted on a robotic arm to generate controlled gradient, rotating, and oscillating fields. The fabrication, characterization, and controlled manipulation of the MSR are systematically investigated, and a reliable complete-wrapping strategy for securing stones of various sizes is developed. Furthermore, we propose and validate a full clinical workflow, including delivery and retrieval strategies in a simulated PCNL environment, thereby demonstrating the clinical potential of the MSR.

2 Overall design and characterization

2.1 Fabrication of the MSR

The fabrication process of the MSR is illustrated in Fig. 1a. First, 1 g of sodium tetraborate (borax) was dissolved in 20 mL of deionized water under mechanical stirring to prepare a 5% (mass fraction) borax solution. Then, 1 g of PVA was added to 20 mL of deionized water and mechanically stirred at 60 °C for 1 h to obtain a 5% (mass fraction) PVA solution. The main chain of PVA contains a large number of hydroxyl groups; by increasing the solution temperature, the degree of hydrolysis of PVA can be enhanced. Subsequently, NdFeB particles (5 μm) were added to the prepared PVA solution and stirred under ultrasonic treatment for 20 min to uniformly disperse the NdFeB particles in the PVA solution. Finally, the PVA/NdFeB solution was vigorously mixed with the borax solution at a 4:1 volume ratio to initiate a cross-linking reaction, thereby obtaining the MSR. Note that MSRs with varying magnetic properties can be prepared by adjusting the amount of NdFeB particles added. An MSR

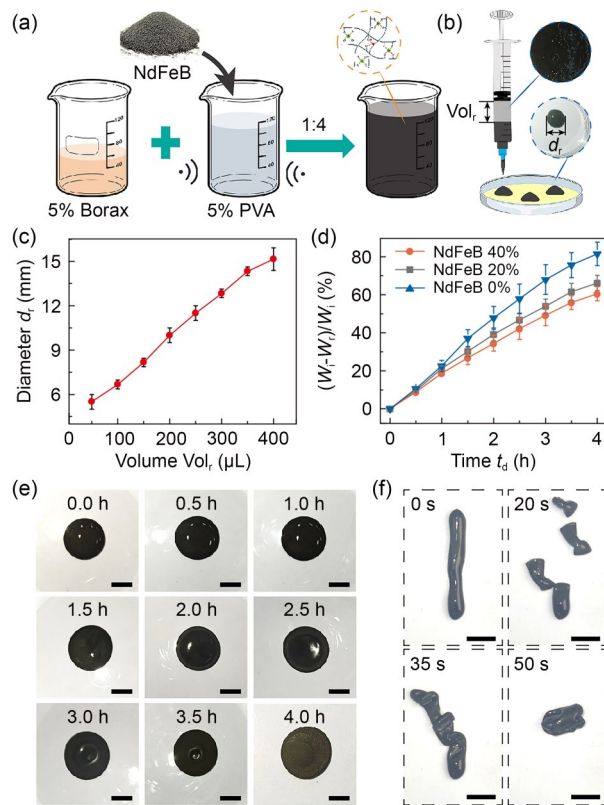


Fig. 1 Fabrication and characterization of the magnetic slime robot (MSR). (a) Schematic of the preparation process for the MSR. (b) Schematic of the extrusion process. (c) Relationship between the volume (Vol_r) and diameter (d_r) of the MSR. (d) Relationship between water content and drying time (t_d) for MSR with different proportions of NdFeB (0%, 20%, and 40%). (e) Optical images of an MSR containing 40% NdFeB during dehydration (scale bars: 5 mm). (f) Self-healing capabilities of an MSR (scale bars: 10 mm). Data in (c, d) are presented as mean $\pm$ standard deviation ($n=3$)

of a specific size can be obtained using the extrusion method as depicted in Fig. 1b.

2.2 Characterization of the MSR

The dimensions, water content, adhesion properties, and magnetization characteristics (magnetic powder ratio and material composition) of the MSR are critical indicators of its functionality, possible application scenarios, and success rates.

2.2.1 Dimensions and water content

Different application scenarios require MSRs of varying sizes. Figure 1c shows the relationship between the volume (Vol_r) and diameter (d_r) of the MSR on a polystyrene (PS) substrate coated with a plant oil film, which is approximately a linear correlation. This study focuses on the transport of kidney stones (typically smaller than 10 mm in size). Therefore, the MSR with a diameter of about 10 mm (and a volume of about 200 μ L) was chosen as a representative object for subsequent

experiments. This size provides a balance: it is (i) small enough to be delivered through a standard percutaneous access sheath, (ii) comparable to or larger than typical target residual fragments (<10 mm) so as to enable effective encapsulation, and (iii) sufficient in magnetic material content for reliable actuation while maintaining maneuverability in confined spaces. Note that the fabrication process allows for scaling to other dimensions as needed for specific anatomy. Over time, the water content of the MSR decreases, as directly evidenced by a reduction in its weight. This dehydration alters key material properties, including the adhesion and deformation capability. Figure 1d presents the relationship between water content and time for MSRs with 10 mm diameter and varying magnetic powder ratios (0%, 20%, and 40%) under conditions of 25 °C and 50% relative humidity (RH), where W_i and W_f represent the initial weight and residual weight of the MSR, respectively. Figure 1d reveals that as the magnetic powder ratio increases, the water loss of the MSR slows down, and the weight loss of the MSR within 1 h is generally less than 20%. After 1.0–1.5 h, the edges of the MSR began to dry and harden, with the drying area gradually encroaching inward. By 4.0 h, it had completely dried to form a sheet-like solid, as shown in Fig. 1e.

Additionally, the MSR exhibits autonomous self-healing capabilities in the absence of external stimulation, a key property that aids its operational robustness. This property allows the MSR to restore its structural integrity in the event of accidental tearing during the procedure. As illustrated in Fig. 1f, when an MSR is divided into four segments and placed together using tweezers, it can re-fuse into a single MSR, demonstrating the outstanding healing ability of the prepared MSR (Video S1 in the supplementary information).

2.2.2 Adhesion property

To investigate the adhesion properties of the MSR, a force sensor (Model LSB201, FUTEK, CA, USA) was used to measure the force required to remove the MSR from different substrates. Figure 2a depicts two retrieval methods: dragging mode and peeling mode, where $V_1=V_2=2$ mm/s. During testing, 300 μ L of the MSR was first dispensed onto the substrate. After a 15-s interval to ensure full contact, the MSR was removed, and the maximum exerted force (F_d or F_p) was recorded. In the dragging mode, the friction force between the drag plate and the substrate must be subtracted. Figure 2b presents optical images of different substrates before and after MSR removal, with corresponding test results shown in Figs. 2c–2f.

As shown in Figs. 2c and 2d, the incorporation of NdFeB particles reduces the adhesion of the MSR, as they hinder the binding between hydroxyl groups on the PVA chains and water molecules. Figures 2e and 2f demonstrate that water loss also significantly diminishes the adhesion of the MSR. Due to

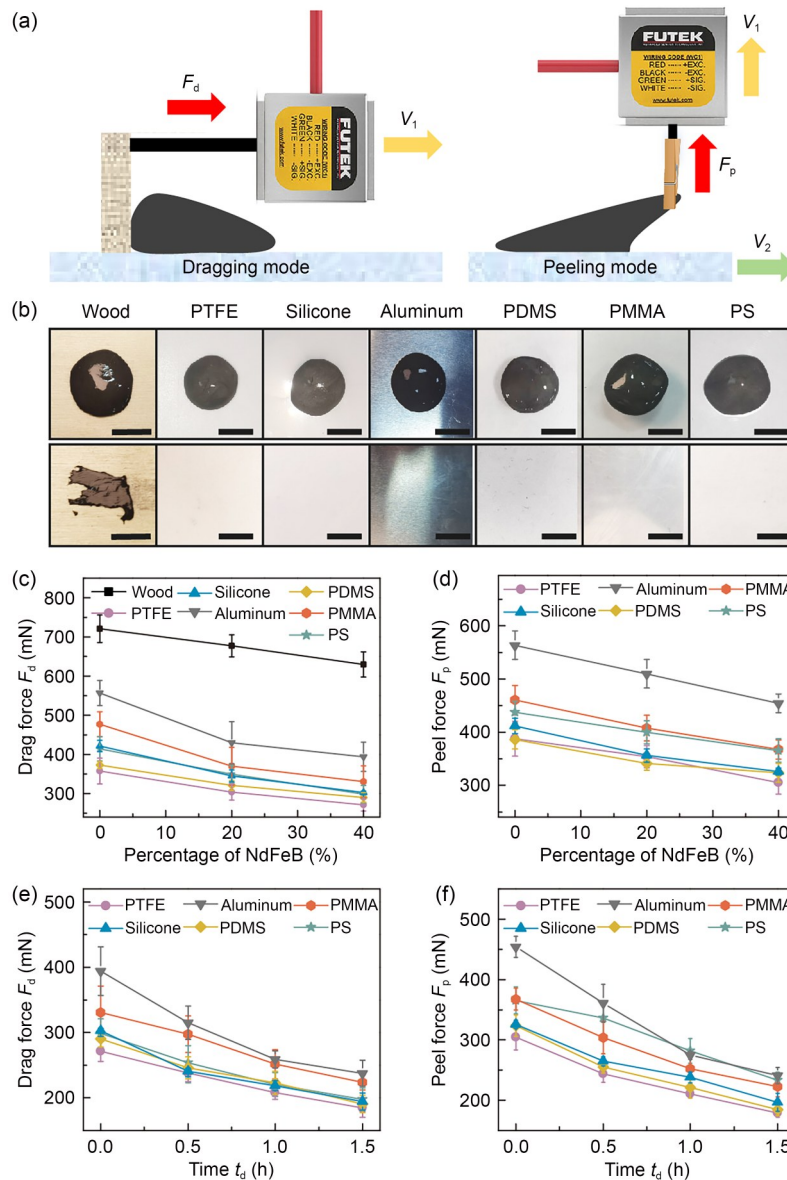


Fig. 2 Adhesion property testing. (a) Schematic of magnetic slime robot (MSR) removal methods: dragging mode and peeling mode. (b) Optical images of different substrates before and after MSR removal (scale bars: 10 mm). (c) Relationship between drag force (F_d) and percentage of NdFeB. (d) Relationship between peel force (F_p) and percentage of NdFeB. (e) Relationship between F_d and drying time (t_d). (f) Relationship between F_p and t_d . Data in (c–f) are presented as mean $\pm$ standard deviation ($n=3$). PTFE: polytetrafluoroethylene; PDMS: polydimethylsiloxane; PMMA: polymethyl methacrylate; PS: polystyrene

the wettability and porous structure of the wood substrate, the MSR can diffuse into its micropores, resulting in substantially higher adhesion on wood substrates compared to other substrates, as shown in Fig. 2c. This also results in residue during the removal process, as seen in Fig. 2b. For aluminum substrates, the synergistic effects of metal chelation and hydrogen bonding lead to superior adhesion performance relative to other substrates, as presented in Figs. 2c–2f. To ensure controllable manipulation, the MSR's adhesion must be moderate. Therefore, subsequent validation experiments were conducted using an MSR with 40% NdFeB and a drying time of 0.5–1.5 h.

2.2.3 Magnetic response

Due to the presence of NdFeB, the MSR enables controllable manipulation under the influence of a magnetic field. To achieve the encapsulation and transport of objects such as stones, excellent deformation capability is required. As presented in Fig. 3a, when the magnetization direction of the NdFeB inside the MSR is misaligned with the external magnetic field, the MSR will experience a magnetic torque m , causing the MSR to undergo curling deformation. To determine the minimum magnetic density (B_{min}) required to induce curling deformation in the MSR, experiments were

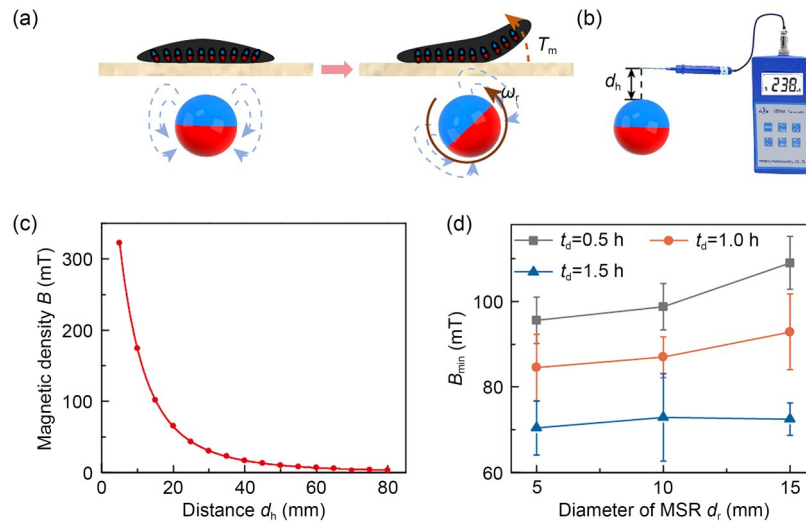


Fig. 3 Magnetic response of the magnetic slime robot (MSR). (a) Schematic of the MSR curling principle. (b) Schematic of magnetic field calibration for the spherical permanent magnet. (c) Relationship between magnetic density and distance for a spherical permanent magnet (N42 grade) with a diameter of 30 mm. (d) Minimum magnetic density (B_{min}) required to drive the MSR with different diameters (5–15 mm) and drying times (0.5–1.5 h). Data in (d) are presented as mean $\pm$ standard deviation ($n=3$)

conducted using a spherical permanent magnet (N42 grade) with a diameter of 30 mm. First, a Gaussmeter (HT201, Hengtong Magnetolectricity Technology Co., Ltd., Shanghai, China) was employed to measure the magnetic field of the spherical permanent magnet, yielding the magnetic field–distance relationship as depicted in Figs. 3b and 3c. Subsequently, the MSR was placed on a polytetrafluoroethylene (PTFE) substrate and gradually curled and rolled for one full turn under the action of the magnetic torque by rotating the spherical permanent magnet. The maximum distance between the magnet and the MSR at which this operation could be performed was recorded. Finally, based on the test results in Fig. 3c, the B_{min} required to drive the MSR to complete this operation was obtained, as presented in Fig. 3d. The experimental results indicate that as drying time (t_d) increases, the adhesion force between the MSR and substrate decreases, leading to a reduction in its minimum driving magnetic density (B_{min}). Additionally, as the diameter of the MSR increases, its minimum driving magnetic density (B_{min}) also grows. From the above experiments, it can be concluded that the driving magnetic field for the MSR must be at least approximately 50 mT, which is difficult to achieve in an electromagnetic coil system.

3 Performance validation of the MSR

3.1 Deformation principles

A hybrid magnetic control system utilizing an electromagnetic coil to drive a permanent magnet was employed, as shown in Fig. 4a; more details on the design are given in Fig. S1 and Table S1 (supplementary information). The

hybrid magnetic actuation system, which is mounted on a robotic arm to ensure a large workspace, integrates a spherical N48 NdFeB permanent magnet (25 mm in diameter, possessing a magnetic dipole moment equivalent to a 30 mm N42 magnet) with an electromagnetic coil array. This configuration has key synergistic advantages: the movable permanent magnet provides the strong spatial field gradients necessary for exerting substantial forces on the viscous MSR, while the electromagnetic coils offer dynamically programmable fields with a frequency response of up to 25 Hz. By merging these capabilities, the system overcomes the limitations of coil-only systems (lacking strong gradients at a distance) and moving-magnet-only systems (limited dynamic bandwidth). This integration enables the generation of multiple magnetic field modes, including gradient, rotating, and oscillating fields, thereby simplifying the control strategy for complex multimodal actuation, as is required in sophisticated tasks such as stone capture and transport in confined spaces. The controlled stretching of the MSR, which is achieved through the synergistic action of magnetic and adhesive forces, enables it to envelop target objects, as illustrated in Fig. 4b. Under a gradient magnetic field, the MSR (with 40% NdFeB) displayed exceptional extensibility, stretching to approximately 5 times its initial length within 45 s, as shown in Fig. 4c and Video S2 (supplementary information). Figure 4d presents the deformation of the MSR under the same conditions as in Fig. 4c but with varying percentages of NdFeB. We can see that the extension ratio of the MSR increases with a higher percentage of NdFeB. Figure 4e investigates the relationship between the tensile capability of the MSR and the percentage of NdFeB under different magnetic fields. These results indicate that the extension ratio of MSR increases with the NdFeB content,

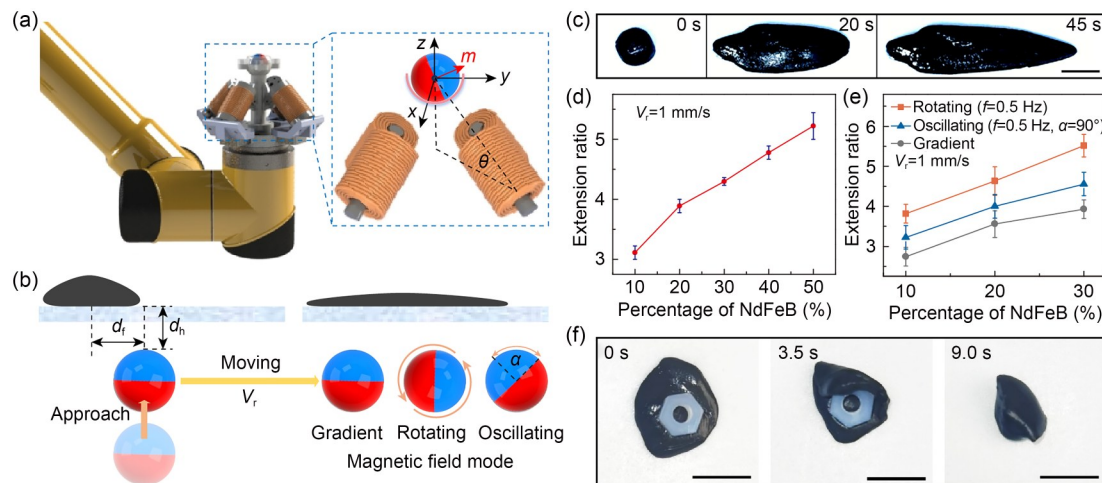


Fig. 4 Deformation principles and testing. (a) Schematic of a magnetic control system utilizing an electromagnetic coil to drive a permanent magnet, wherein the spherical permanent magnet (N48 grade) has a diameter of 25 mm. (b) Schematic of the magnetic slime robot (MSR) stretching process. (c) Optical images of the tensile process of an MSR with 40% NdFeB under a gradient magnetic field. (d) Relationship between the extension ratio of the MSR and percentage of NdFeB under $V_r=1$ mm/s. (e) Relationship between the extension ratio of the MSR and percentage of NdFeB, under $V_r=1$ mm/s and different drive magnetic field modes. (f) Optical images of the encapsulation of a target object by the MSR in a rotating magnetic field. Scale bars: 10 mm. Data in (d, e) are presented as mean $\pm$ standard deviation ($n=3$)

reaching its maximum under a rotating magnetic field. Owing to the curling deformation of the MSR under magnetic torque, it can be applied to grasp and wrap target objects. Figure 4f illustrates the process of using an MSR to wrap around an M4 nylon nut via curling deformation. Under the influence of the magnetic torque, one end of the MSR begins to curl inward, gradually enveloping the nut. After the spherical permanent magnet rotates 180°, the MSR can carry the nut and lift completely (Video S2 in the supplementary information).

3.2 Movement controllability and environmental adaptability

Movement controllability and environmental adaptability are key indicators for the MSR in terms of its ability to execute complex tasks. Figure 5a shows the trajectories of the MSR moving along the “M” (PTFE), “R” (polydimethylsiloxane (PDMS)), “T” (Al), and “U” (silicone) paths on different substrates under a gradient magnetic field (Video S3 in the supplementary information). A slight stretching deformation is particularly clear during the curved “R” trajectory, in contrast to the more uniform sliding locomotion seen in the straight-line segments (“M,” “T,” “U”). This discrepancy stems from the distinct motion profiles of the robotic arm. For straight paths, the arm executes constant-velocity linear motion, which maintains the MSR in a steady, slightly-stretched equilibrium state, and results in predominant sliding. In contrast, tracing the curved “R” path requires interpolated motion, involving inherent accelerations and directional changes. These kinematic variations create brief intervals where the magnetic force balance shifts, allowing the viscoelastic MSR to momentarily relax and recover its shape,

and thereby making the stretching phase visible during curved motion. Motion control of the MSR is fundamentally achieved by the magnetic force and torque acting on the randomly dispersed NdFeB particles within its matrix. The MSR itself lacks a net macroscopic magnetization unless aligned by a strong external field. The substrate influences locomotion primarily via adhesive interaction, as illustrated in Fig. 2. Substrates with lower adhesion (e.g., PTFE) facilitate easier sliding. The successful trajectory tracing on substrates with varying adhesion (PTFE, PDMS, Al, silicone) demonstrates the system’s capability to overcome different interfacial forces through appropriate magnetic field control, underscoring the environmental adaptability of the proposed technology.

Figure 5b presents the trajectory of the MSR capturing a stone with a diameter of 3 mm and transporting it along an “L” path under a rotating magnetic field ($f=0.5$ Hz), showcasing the MSR’s exceptional motion controllability and its capability for targeted capture and transport (Video S3 in the supplementary information). The MSR also possesses excellent passive deformation capabilities, enabling it to adapt to complicated terrain and enter confined spaces in a controlled manner while maintaining mobility and structural integrity; in this way, it can better fulfill requirements of multiple missions. As shown in Figs. 5c1 and 5c2, the MSR can smoothly traverse channels of varying widths (2.5–5.0 mm) and navigate complex mazes with a minimum gap of 2.5 mm under a gradient magnetic field. Additionally, the MSR can traverse uneven surfaces in a rolling mode under a rotating magnetic field, which demonstrates its ability to adapt to diverse terrains through different motion modes; as such, there is minimal environmental interference and its potential applications are vast, as shown in Fig. 5c3 and Video S3 (supplementary information).

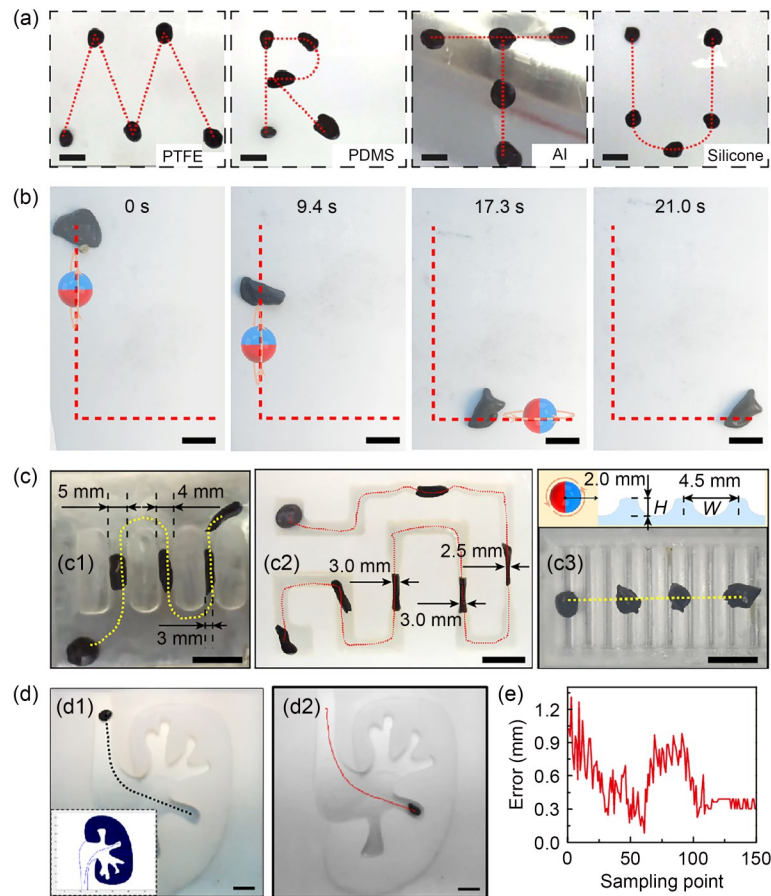


Fig. 5 Movement controllability and environmental adaptability. Motion trajectory of the magnetic slime robot (MSR) along the specific trajectories on different substrates: without load (a) and capturing a 3 mm stone (b). (c) Passive deformation and multimodal motion of the MSR. (d) Path planning (d1) and the navigation trajectory (d2) of the MSR along the planned path. (e) Tracking error of the MSR trajectory shown in (d). Scale bars: 10 mm

To further investigate the movement controllability and targeted movement accuracy of the MSR, the A* algorithm was employed to conduct path planning and autonomous motion experiments for the MSR with a diameter of 6 mm on a silicone kidney model, as illustrated in Fig. 5d and Video S3 (supplementary information). Figure 5e shows the error between the actual motion trajectory and the planned path; the results indicate a maximum trajectory tracking error of 1.3 mm for the MSR, which is less than 25% of its diameter, demonstrating excellent motion control accuracy. This level of tracking accuracy is clinically significant, indicating that the MSR can be controlled with sufficient precision, and is feasible for both surgeon-guided and pre-planned image-guided control.

3.3 Capture and transport of kidney stones

The inherent adhesiveness and stretch-based wrapping capability of the MSR are key to achieving reliable capture and transport of target objects. Figure 6a illustrates the target capture and transport strategy. First, the MSR approaches the target object in a rotational mode and covers it to complete

the capture (i→ii). Then, the spherical permanent magnet is brought near the MSR to enhance the adhesion between it and the target object (ii). Subsequently, the MSR is flipped 180° by the rotating magnetic field, thereby exposing the target object on its surface (iii). Finally, the MSR is stretched and curled from one end so as to fully encapsulate the target object (iv→vi). Figure 6b demonstrates the capture, encapsulation, and transport of a stone with a size of approximately 8 mm using an MSR with a diameter of 10 mm, using the strategy illustrated in Fig. 6a and Video S4 (supplementary information). Based on the typical density range of urinary calculi (1.6–2.0 g/cm³) [35], the target stone fragments (<10 mm) have an estimated weight of less than 1 g. The MSR demonstrated successful transport capability for stones up to 8 mm in diameter, indicating its suitability for the intended clinical load scale. Figures 6c and 6d illustrate the treatment process for multiple small stones (<5 mm) at the same location and at different locations using an MSR with a diameter of 10 mm (Video S4 in the supplementary information). For small stones at the same location, the MSR can completely encapsulate the target object by repeatedly bonding

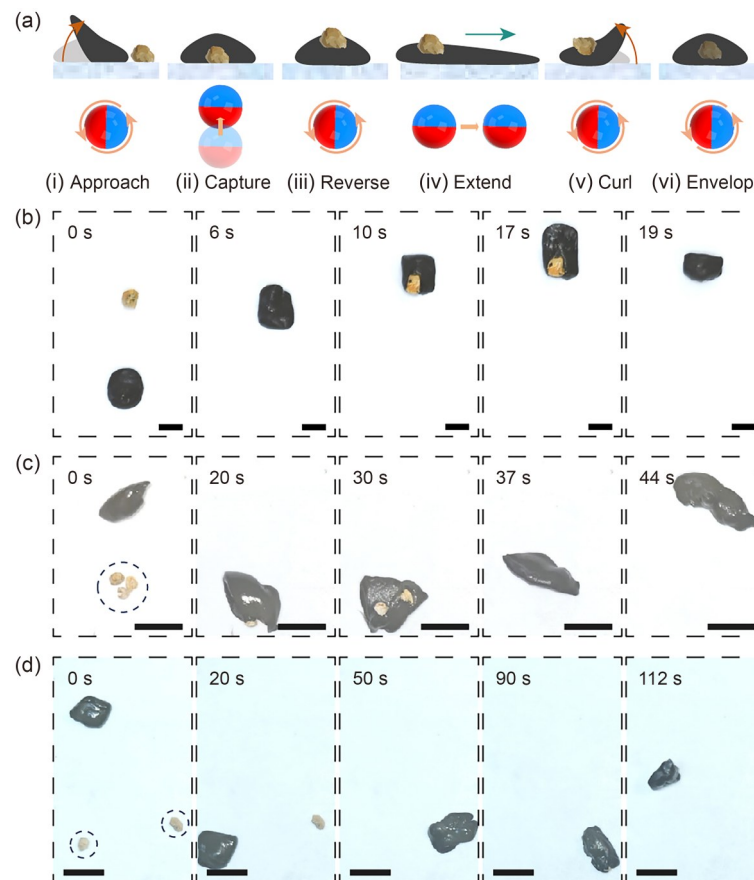


Fig. 6 Capture, encapsulation, and transport of a stone. (a) Schematic of the magnetic slime robot (MSR)'s working process. (b–d) Optical images of different stones treated by an MSR with a diameter of 10 mm: (b) a single stone approximately 8 mm in size; (c) multiple small stones (<5 mm) at the same location; (d) two small stones (<5 mm) spaced 25 mm apart. Scale bars: 10 mm

the coiled end to the non-coiled end during its rolling motion. For small stones located at different positions, the MSR sequentially captures, encapsulates, and transports them based on the previous procedure. Each of the above operations can generally be completed within 60 s without causing the target object to detach, demonstrating the reliability of the strategy.

4 In vitro application of the MSR

4.1 Delivery and recycling

PCNL is one of the modern minimally invasive techniques for treating kidney stones. PCNL requires creating a pathway from the skin to the kidney in the flank region. Through this pathway, a nephroscope is inserted into the kidney, wherein lithotripsy instruments such as lasers or ultrasonic devices are used to break up kidney stones. The proposed MSR aims to replace traditional suction techniques for stone retrieval during PCNL. Therefore, the MSR must be delivered to the designated location and be recycled after completing its assigned task. We employed a guidewire to facilitate the delivery and

recycling of the MSR during PCNL, as shown in Figs. 7a and 7c, leveraging its inherent adhesive and magnetic response properties. Figure 7b illustrates the delivery process of the MSR in a silicone-molded kidney puncture model (Video S5 in the supplementary information). First, an appropriate amount of MSR is wrapped around the tip of the guidewire and placed inside the catheter sheath for insertion into the kidney via a nephrostomy tube. Once the MSR reaches the target location, the outer sheath is held still while the guidewire is withdrawn. Simultaneously, a gradient magnetic field is applied to pull the MSR outward, releasing it from the sheath. Experimental findings demonstrate that this method can accurately deliver the MSR to the target location within 1 min.

Figure 7c depicts the recycling strategy for the MSR, wherein a rotating magnetic field is applied to curl the MSR around the guidewire. To minimize the radial dimensions of the guidewire after MSR encapsulation and prevent fracturing or detachment during MSR recycling, magnetized guidewires were designed as shown in Figs. 7c2 and 7c3. The results demonstrate that the magnetization direction of the magnetic guidewire significantly influences the retrieval efficiency

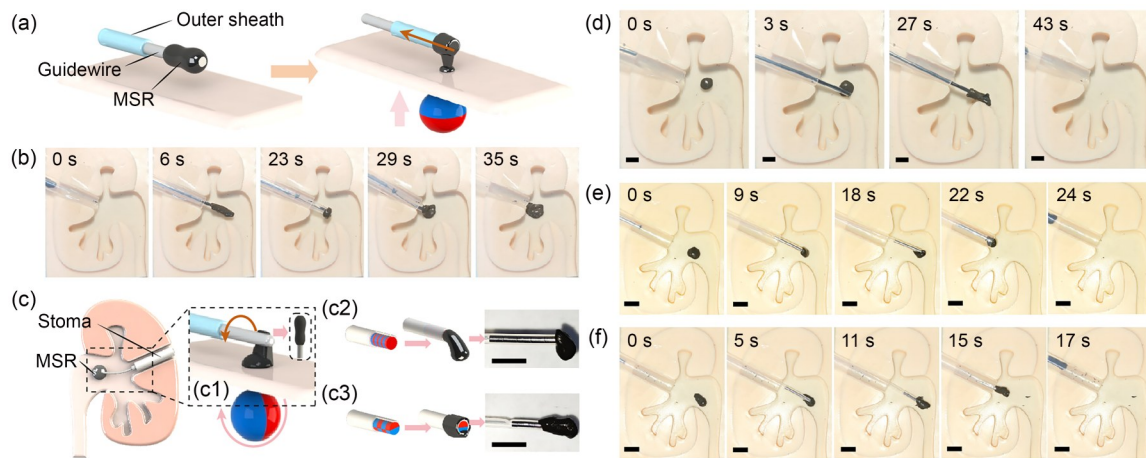


Fig. 7 Delivery and collection of the magnetic slime robot (MSR). (a) Schematic of the MSR delivery strategy. (b) Optical images of MSR delivery. (c) Schematic of the MSR recycling strategy: (c1) conventional non-magnetic guidewire; (c2) axially magnetized guidewire; (c3) radially magnetized guidewire. (d–f) Optical images of MSR collection: (d) conventional non-magnetic guidewire; (e) axially magnetized guidewire; (f) radially magnetized guidewire. Scale bars: 10 mm

of the MSR. Compared to axially magnetized guidewires, radially magnetized guidewires exhibit superior recycling performance, which primarily manifests in smaller radial dimensions. Figures 7d–7f respectively illustrate the recycling processes of the MSR using conventional non-magnetic guidewires, axially magnetized guidewires, and radially magnetized guidewires, demonstrating that the recycling time achieved with the radially magnetized guidewire is only 40% of that required by the conventional guidewire. The enhanced retrieval efficiency of the radially magnetized guidewire is attributed to its magnetic field geometry. A radially magnetized cylinder generates a magnetic field that emanates outward from its entire circumferential surface. This creates a larger and more uniform attractive area along the guidewire's length, facilitating more rapid and compact curling and bundling of the MSR around it. In contrast, an axially magnetized guidewire has its magnetic field concentrated primarily at its poles, resulting in less efficient and less uniform attraction along its shaft; therefore, subsequent experiments were conducted using the radially magnetized guidewire.

4.2 In vitro biomedical applications

During PCNL, different patient positionings are required based on stone location, which affects the angle between the kidney and the horizontal plane. Accordingly, to ensure the feasibility of MSR manipulation across multiple positions, the scenario depicted in Fig. 8a was constructed to evaluate the MSR's mobility on non-horizontal surfaces, wherein the MSR moves in a flipping mode ($f=1$ Hz). Figure 8b shows the relationship between the MSR's maximum speed ($V_{\max}$) and drive distance (d_h) across different inclines (30° – 90°). On a typical 45° slope, the MSR can move at a speed of approximately 5 mm/s at $d_h=20$ mm. These results demonstrate

that the MSR is capable of locomotion on non-horizontal surfaces, satisfying the mobility requirements for operation in various anatomical postures. Moreover, Fig. 8c illustrates the relationship between the MSR's maximum speed ($V_{\max}$) and slope angle (θ) under varying load conditions. While the MSR's maximum speed decreases with increasing load, its motion performance on inclined surfaces remains largely unaffected.

Figure 8d shows the experiment where the MSR was used to remove kidney stones in a kidney model, which can be completed within 3 min (Video S6 in the supplementary information). First, multiple kidney stones ranging from 1–3 mm in size were placed at the ureteral port of the kidney model, in order to simulate the state of large stones after lithotripsy treatment via shock wave lithotripsy or laser lithotripsy. Next, the MSR was delivered to the vicinity of the stones in approximately 45 s. Subsequently, the MSR was controlled to curl and extend toward the stones until they were fully covered under the rotating magnetic field. Once the stones were completely attached to the MSR, a reverse rotating magnetic field was applied to the MSR, causing it to coil backward into a bundle, thereby encapsulating the fragmented stones within the bundle. Finally, the MSR carrying the stones was moved to the appropriate position, and recycled using a magnetic guidewire.

To further validate the clinical feasibility of the MSR for kidney stone retrieval, ex vivo experiments on stone capture and transport were conducted using a porcine kidney model, as shown in Fig. 8e; here, the MSR used had a diameter of approximately 10 mm (Video S6 in the supplementary information). First, a fresh porcine kidney was medially sectioned to expose its internal structure, and a 3 mm kidney stone was placed at its renal pelvis location. Subsequently, an MSR was positioned within the renal pelvis and maneuvered to roll toward the stone. The MSR then captured and encapsulated the stone using the strategy illustrated in Fig. 6.

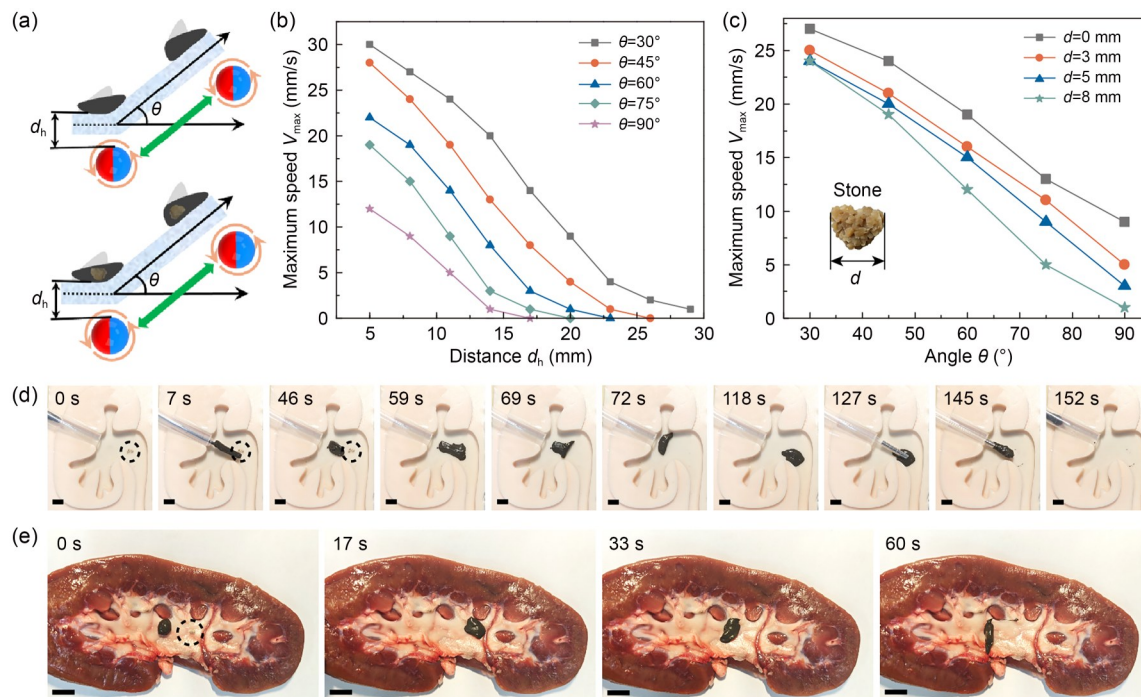


Fig. 8 In vitro biomedical applications. (a) Schematic of magnetic slime robot (MSR) climbing. (b) The relationship between the MSR's maximum speed (V_{max}) and drive distance (d_h) across different inclines. (c) The relationship between V_{max} and slope angle (θ) under varying load conditions. (d) The entire process of MSR delivery, stone capture, and transport, and MSR recycling in a kidney model. (e) Optical images of stone capture and transport in an in vitro kidney. Scale bars: 10 mm

Finally, the MSR was retracted to its initial position. These experimental findings demonstrate the clinical potential of the proposed method.

5 Discussion and conclusions

This work presents an MSR specifically engineered for minimally invasive retrieval of residual kidney stones, surpassing prior demonstrations of magnetic soft robots by integrating a tailored hybrid magnetic actuation system and a clinical workflow for PCNL. The MSR leverages a bio-inspired PVA–borax matrix with NdFeB particles, achieving exceptional deformability, autonomous self-healing, and controllable adhesion. Critically, the hybrid actuation system, which uniquely combines a spherical permanent magnet with electromagnetic coils on a robotic arm, overcomes the typical trade-offs of standalone coil arrays (weak gradients) and moving-magnet systems (low dynamic response), thereby enabling precise multimodal manipulation under programmable gradient, rotating, and oscillating fields. Experiments demonstrate that the MSR stretches approximately $5\times$ its initial length, navigates 2.5 mm gaps, and tracks paths with ≤ 1.3 mm error. In vitro validation in silicone kidney models and porcine tissues confirms the efficient capture and transport of stones up to 8 mm in size within 3 min, while magnetized guidewires reduce the retrieval time by 60% compared to

conventional methods. These results highlight the MSR's potential to address post-PCNL stone retention, overcoming the limitations of existing minimally invasive retrieval technologies.

While the presented results validate the core functionalities of the MSR for stone retrieval, a few aspects warrant further discussion, particularly with regard to its translational potential and future development. First, concerning the scalability and limitations of the method, the current strategy demonstrates efficacy for targeted fragments in the size range of 2–10 mm, as was shown with the 8 mm stone retrieval using a 10 mm MSR. Scaling to retrieve significantly larger solitary fragments (>15 mm) would require a proportionally larger MSR, which may present challenges for delivery through standard percutaneous access sheaths; a possible alternative is sequential retrieval after further fragmentation. Conversely, in the case where there is a high quantity of sub-millimeter debris, while the MSR's adhesive surface allows collective capture via sweeping, irrigation may be more efficient for complete clearance of such debris. Second, the self-healing property of the MSR is not merely a material characteristic, but a critical functional safety feature for in vivo applications. It ensures that incidental tearing during navigation or stone interaction does not lead to irretrievable material loss within the kidney, thereby enhancing procedure safety. Third, due to its inherent adhesiveness, the MSR may leave minimal traces on tissues—an important consideration for clinical

translation. Future iterations of work could fine-tune the adhesion–recovery balance, for example through particle surface modification (e.g., silica coating) or matrix formulation optimization, so as to minimize potential residue while preserving essential function. Finally, while this study focused on macroscale robotic functionality and validation, a detailed rheological characterization of the field-dependent viscoelasticity (e.g., measuring storage modulus and loss modulus under magnetic fields) would be valuable for future fundamental material research, potentially informing more advanced control models.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1631/bdm.2600137>.

Acknowledgements This work was supported in part by the National Key R&D Program of China (No. 2023YFB4705600), in part by the National Natural Science Foundation of China (Nos. 62573154 and U25A20476), and in part by the Natural Science Foundation of Heilongjiang Province of China (No. YQ2024F011).

Author contributions HZ and FHW were involved in conceptualization and in writing the original draft. FHW conducted the main experiments. HZ and JSZ assisted in the investigation and experiments. HZ and HX helped revise the paper, supervised the work, and applied for funds. All authors have read and approved this manuscript for publication.

Declarations

Conflict of interest HX is a guest editor of the Special Column on Magnetic Control Devices and Their Biomedical Applications of *Bio-Design and Manufacturing*; he was not involved in the editorial review or the decision to publish this article. The authors declare that they have no conflict of interest.

Ethical approval This study used an ex vivo porcine kidney procured from a commercial supplier (Harbin, China), and no live animal experiments were conducted. The use of these tissues did not require ethical review as per institutional guidelines.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Use of generative AI tools No generative AI tools were used in this study.

References

- Alelign T, Petros B (2018) Kidney stone disease: an update on current concepts. *Adv Urol* 2018:3068365. <https://doi.org/10.1155/2018/3068365>
- Miller NL, Lingeman JE (2007) Management of kidney stones. *BMJ* 334(7591):468–472. <https://doi.org/10.1136/bmj.39113.480185.80>
- Kang DE, Maloney MM, Haleblan GE et al (2007) Effect of medical management on recurrent stone formation following percutaneous nephrolithotomy. *J Urol* 177(5):1785–1789. <https://doi.org/10.1016/j.juro.2007.01.061>
- Harper JD, Cunitz BW, Dunmire B et al (2016) First in human clinical trial of ultrasonic propulsion of kidney stones. *J Urol* 195(4 Part 1):956–964. <https://doi.org/10.1016/j.juro.2015.10.131>
- Cloutier J, Cordeiro ER, Kamphuis GM et al (2014) The glue-clot technique: a new technique description for small calyceal stone fragments removal. *Urolithiasis* 42(5):441–444. <https://doi.org/10.1007/s00240-014-0679-7>
- Hein S, Schoeb DS, Grunwald I et al (2018) Viability and biocompatibility of an adhesive system for intrarenal embedding and endoscopic removal of small residual fragments in minimally-invasive stone treatment in an in vivo pig model. *World J Urol* 36(4):673–680. <https://doi.org/10.1007/s00345-018-2188-8>
- Tan YK, McLeroy SL, Faddegon S et al (2012) In vitro comparison of prototype magnetic tool with conventional nitinol basket for ureteroscopic retrieval of stone fragments rendered paramagnetic with iron oxide microparticles. *J Urol* 188(2):648–652. <https://doi.org/10.1016/j.juro.2012.03.118>
- Sur RL, Agrawal S, Eisner BH et al (2022) Initial safety and feasibility of steerable ureteroscopic renal evacuation: a novel approach for the treatment of urolithiasis. *J Endourol* 36(9):1161–1167. <https://doi.org/10.1089/end.2021.0759>
- Tang W, Gao YD, Dong ZY et al (2024) Sustainable and untethered soft robots created using printable and recyclable ferromagnetic fibers. *Bio-Des Manuf* 7(6):926–937. <https://doi.org/10.1007/s42242-024-00303-4>
- Niu FZ, Xue QH, Cao Q et al (2025) Magneto-soft robots based on multi-materials optimizing and heat-assisted in-situ magnetic domains programming. *Int J Extrem Manuf* 7(5):055506. <https://doi.org/10.1088/2631-7990/add81b>
- Hao CL, Dou BH, Yang SH et al (2025) Bio-inspired magnetic soft robot with dual-modal locomotion for enhanced liquid–air interface navigation. *Bio-Des Manuf* 8(6):1024–1034. <https://doi.org/10.1631/bdm.2500047>
- Lu HJ, Zhang M, Yang YY et al (2018) A bioinspired multi-legged soft millirobot that functions in both dry and wet conditions. *Nat Commun* 9:3944. <https://doi.org/10.1038/s41467-018-06491-9>
- Serwane F, Mongera A, Rowghanian P et al (2017) In vivo quantification of spatially varying mechanical properties in developing tissues. *Nat Methods* 14(2):181–186. <https://doi.org/10.1038/nmeth.4101>
- White TJ, Broer DJ (2015) Programmable and adaptive mechanics with liquid crystal polymer networks and elastomers. *Nat Mater* 14(11):1087–1098. <https://doi.org/10.1038/nmat4433>
- Li C, Iscen A, Sai H et al (2020) Supramolecular–covalent hybrid polymers for light-activated mechanical actuation. *Nat Mater* 19(8):900–909. <https://doi.org/10.1038/s41563-020-0707-7>
- Zhao YS, Hua MT, Yan YC et al (2022) Stimuli-responsive polymers for soft robotics. *Annu Rev Control Robot Auton Syst* 5:515–545. <https://doi.org/10.1146/annurev-control-042920-014327>
- Xu ZC, Chen YH, Xu QS (2023) Spreadable magnetic soft robots with on-demand hardening. *Research* 6:262. <https://doi.org/10.34133/research.0262>
- Mao LY, Tian CY, Yang P et al (2025) Swarm coordination of fish-like magnetic soft robots: directed aggregation and shape-adaptive attachment toward efficient drug delivery. *Natl Sci Rev* 12(12):nwaf429. <https://doi.org/10.1093/nsr/nwaf429>
- Hu WQ, Lum GZ, Mastrangeli M et al (2018) Small-scale soft-bodied robot with multimodal locomotion. *Nature* 554(7690):81–85. <https://doi.org/10.1038/nature25443>
- Du XZ, Yu JF (2023) Image-integrated magnetic actuation systems for localization and remote actuation of medical miniature

- robots: a survey. *IEEE Trans Robot* 39(4):2549–2568. <https://doi.org/10.1109/TRO.2023.3271582>
21. Cao Q, Pan Y, Zhang YQH et al (2025) A dual-functional capsule robot for drug delivery and tissue biopsy based on magnetic torsion spring technology. *Bio-Des Manuf* 8(3):495–510. <https://doi.org/10.1631/bdm.2400276>
 22. Wang QQ, Xiang N, Lang J et al (2024) Reconfigurable liquid-bodied miniature machines: magnetic control and microrobotic applications. *Adv Intell Syst* 6(2):2300108. <https://doi.org/10.1002/aisy.202300108>
 23. Zhao ZB, Soni S, Lee T et al (2023) Smart eutectic gallium–indium: from properties to applications. *Adv Mater* 35:2203391. <https://doi.org/10.1002/adma.202203391>
 24. Fan XJ, Dong XG, Karacakol AC et al (2020) Reconfigurable multifunctional ferrofluid droplet robots. *Proc Natl Acad Sci USA* 117(45):27916–27926. <https://doi.org/10.1073/pnas.2016388117>
 25. Wang QY, Pan CF, Zhang YX et al (2023) Magnetoactive liquid-solid phase transitional matter. *Matter* 6(3):855–872. <https://doi.org/10.1016/j.matt.2022.12.003>
 26. Shen YF, Jin DD, Fu MM et al (2023) Reactive wetting enabled anchoring of non-wettable iron oxide in liquid metal for miniature soft robot. *Nat Commun* 14:6276. <https://doi.org/10.1038/s41467-023-41920-4>
 27. Fan XJ, Jiang YH, Li MT et al (2022) Scale-reconfigurable miniature ferrofluidic robots for negotiating sharply variable spaces. *Sci Adv* 8(37):eabq1677. <https://doi.org/10.1126/sciadv.abq1677>
 28. Sun MM, Hao B, Yang SH et al (2022) Exploiting ferrofluidic wetting for miniature soft machines. *Nat Commun* 13:7919. <https://doi.org/10.1038/s41467-022-35646-y>
 29. Zhang WW, Deng YG, Zhao JH et al (2023) Amoeba-inspired magnetic venom microrobots. *Small* 19(23):2207360. <https://doi.org/10.1002/sml.202207360>
 30. Sun MM, Tian CY, Mao LY et al (2022) Reconfigurable magnetic slime robot: deformation, adaptability, and multifunction. *Adv Funct Mater* 32(26):2112508. <https://doi.org/10.1002/adfm.202112508>
 31. Li M, Pal A, Byun J et al (2023) Magnetic putty as a reconfigurable, recyclable, and accessible soft robotic material. *Adv Mater* 35(48):2304825. <https://doi.org/10.1002/adma.202304825>
 32. Akkanapalli U, Gundam BR, Kandenelly S et al (2024) Minimally invasive therapy for retrieval of ingested foreign bodies in GI tract using magnetic slime. 2nd International Conference on Emerging Trends in Engineering and Medical Sciences, p.356–360. <https://doi.org/10.1109/ICETEMS64039.2024.10965049>
 33. Xiang YX, Jin CY, Wang WB et al (2026) Enable active mobility of untethered miniature robots in high-resistance multiphase medium. *Sci Adv* 12(9):eaea7188. <https://doi.org/10.1126/sciadv.aea7188>
 34. Zhang H, Luo KD, Wang FH et al (2025) Development of a magnetically-actuated capsule robot for biopsy sampling using SMA. *J Bionic Eng* 22(4):1609–1621. <https://doi.org/10.1007/s42235-025-00734-4>
 35. Liu YG, Su LJ (2024) Responses of ureteral pain caused by small-sized kidney stones under fluid-structure coupling. *Appl Math Mech* 45(6):735–752. <https://doi.org/10.21656/1000-0887.450095>