



Magnetic frequency-controlled mode-switchable flexible microrobot enabling adaptive locomotion in biological channels for targeted drug delivery

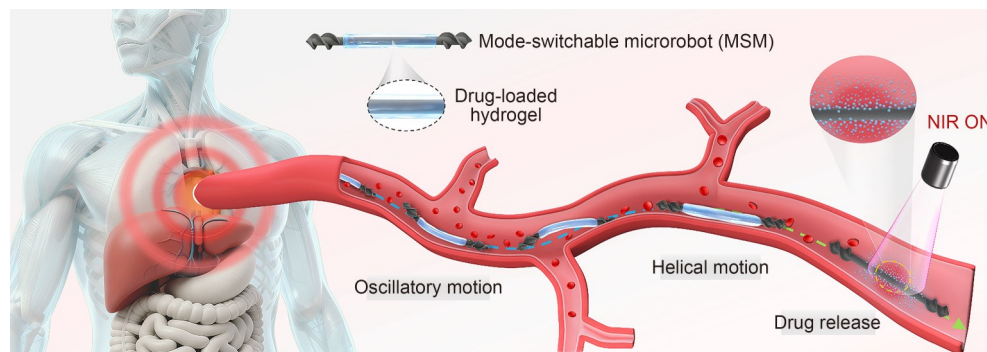
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Abstract

Magnetic microrobots hold immense potential for various biomedical applications, including targeted drug delivery. However, their operational efficacy in complex, heterogeneous biological environments (e.g., vasculature with varying lumen diameters) is often constrained. To address this limitation, this study presents a magnetically driven soft microrobot capable of dual-mode locomotion, where seamless switching between oscillatory and helical motions is achieved solely by switching the external magnetic field frequency via frequency modulation. The proposed microrobot, with a millimeter-scale architecture featuring a programmed magnetization profile, exhibits C-shaped oscillation at low frequencies for rapid propulsion and terrain adaptation, and transforms into a helical rotation at high frequencies for stable navigation within confined channels. Experiments were conducted in a glycerol–water mixture to reveal that oscillatory and helical motion modes each operate within distinct, non-overlapping frequency bands. The microrobot successfully performed navigation through mode switching in both a bio-mimetic vascular model and ex vivo porcine organs. Furthermore, by integrating a photothermal-responsive methacrylated gelatin (GelMA) drug carrier, we demonstrated successful targeted drug delivery at a designated site triggered by near-infrared irradiation after magnetically guided delivery in a dynamic flow environment.

Graphical abstract



Keywords Magnetically driven · Soft microrobot · Dual-mode locomotion · Frequency modulation · Targeted drug delivery

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1 Introduction

Microrobots have emerged as a prominent research field owing to their extensive application prospects in biomedicine, demonstrating particularly high potential in targeted drug delivery [1], minimally invasive surgery [2–4], and in vivo precision diagnosis [5, 6]. Compared with traditional rigid robots, soft microrobots exhibit excellent biocompatibility, structural compliance, and environmental adaptability, enabling safe and efficient operation within complex and dynamic environments [7–9]. The continued progress in micro/nanofabrication and smart materials requires fostering innovations in the design and actuation of soft microrobots, thereby accelerating their translation from laboratory research toward clinical practice [10–15].

The motion of soft microrobots typically relies on external stimuli for precise control [16–24]. Among the various actuation strategies derived so far, magnetic actuation has been extensively utilized for in vivo microoperations due to its superior biosafety, high spatiotemporal resolution, and deep-tissue penetration capability. Through a sophisticated structural and magnetization design, such microrobots can achieve diverse motion modes under programmable magnetic fields to accommodate varying environmental constraints and functional demands [25–28]. For example, a multi-material optimization and thermally assisted in-situ magnetic domain programming method was proposed, which enhances the material properties and manufacturing efficiency of magneto-soft robots [29]. Nelson and colleagues developed a magnetically guided microrobot platform for targeted drug delivery, whose efficacy has been validated through both in vitro experiments and in vivo trials on large animals [15].

Based on the specific motion mechanism, magnetically actuated microrobots are capable of diverse motion modes, mainly including oscillatory swimming, helical propulsion, crawling, and rolling [30–32]. Among these, oscillatory swimming and helical motion present significant advantages in various scenarios due to the associated unique dynamic characteristics. Oscillatory swimming mimics the propulsion mechanism of fish or ciliates, generating asymmetric drag in fluids through periodic oscillations of the entire body or local segments to achieve efficient propulsion [33, 34]. This mode is characterized by high speed, flexible steering, and robust terrain adaptability, making it ideal for open or semi-confined environments. In contrast, helical motion imitates the rotation mechanism of bacterial flagella, producing propulsive force through the interaction between the helical structure and surrounding fluids. Thus, it is particularly suitable for narrow and high-resistance tubular environments, with merits such as high motion stability, controllable direction, and insensitivity to flow disturbances [35, 36].

However, the in vivo environment possesses high complexity and heterogeneity. The vascular system, for instance,

contains both large-diameter lumens and extremely narrow microvessels, accompanied by multiple challenges such as branching, bending, and dynamic blood flow [37]. When operating in such variable environments, microrobots with a single locomotion mode often suffer from performance limitations. To enhance their operational reliability in such dynamic biological milieus, existing studies have attempted to achieve multimodal locomotion through structural design or complex control methods, and these approaches typically rely on sophisticated control systems or the coupling of multiple physical fields [38, 39]. However, this not only increases the difficulty of system integration and operation but may also introduce energy interference and positioning errors in practical applications.

In this work, a mode-switchable microrobot (MSM) was developed and proposed. Through specific magnetization distribution and structural design, the MSM achieves rapid and reliable switching between oscillatory and helical modes by adjusting the frequency of the oscillating magnetic field. As illustrated in Fig. 1a, the MSM exhibits fish-like oscillatory motion at low frequencies for rapid propulsion and obstacle crossing, while it transitions into helical rotation at high frequencies for stable navigation within confined flow channels. Furthermore, methacrylated gelatin (GelMA) with photothermal response properties is integrated as a drug carrier on the MSM surface, enabling on-demand drug release triggered by near-infrared (NIR) irradiation. Systematic experiments in bionic vascular models and ex vivo biological tissues demonstrate that the MSM not only exhibits excellent motion performance and environmental adaptability but also successfully accomplishes a series of tasks including multi-path navigation, targeted delivery, and NIR-triggered drug release. This research provides a novel design and control paradigm for developing intelligent microrobotic systems capable of adapting to complex biological environments.

2 Materials and methods

2.1 Materials

The magnetic soft body of the microrobot was fabricated from a composite of polydimethylsiloxane (PDMS; Sylgard 184, Dow Corning, Midland, USA) and neodymium iron boron (NdFeB; YMM-15-7, Yuhong Magnetic Materials Co., Ltd., Jiangmen, China) powder with a particle size of 165 μm , while the drug carrier was a GelMA (EFL-GM-30, Yongqinquan Intelligent Equipment Co., Ltd., Suzhou, China) film. The PDMS (with a base-to-curing agent ratio of 10:1) and the NdFeB powder (with a maximum energy product of 115–123 kJ/m^3) were integrated to form the actuator matrix. The GelMA (with a methacrylation degree of approximately 30%) was subsequently processed into a film to function as the drug carrier.

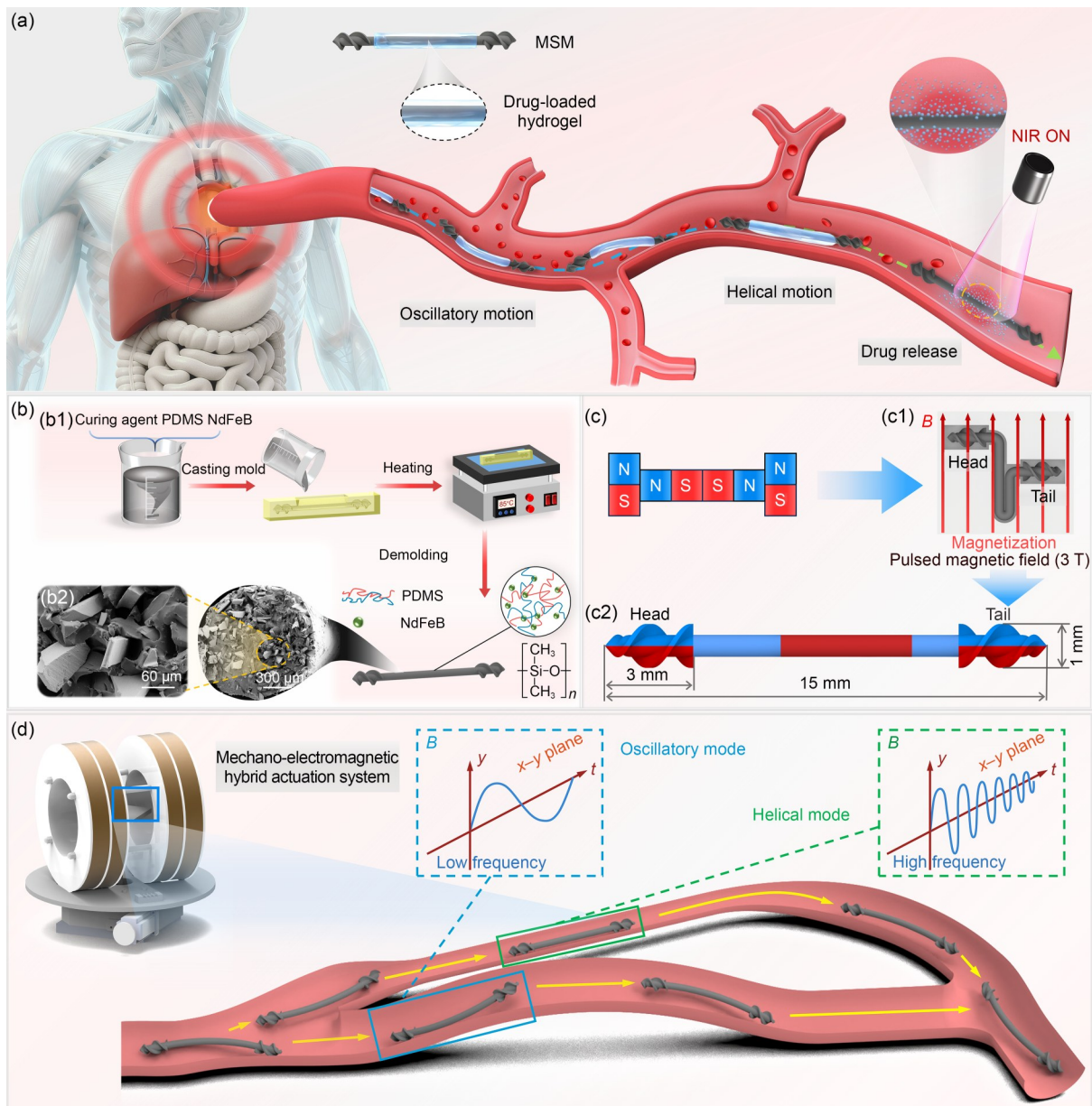


Fig. 1 Mode-switchable microrobot (MSM). (a) Schematic illustration of the motion and function of the MSM. (b) Fabrication and characterization of the MSM: (b1) fabrication process of the MSM; (b2) cross-sectional scanning electron microscopy (SEM) image of the MSM. (c) Magnetization strategy and final structure of the MSM: (c1) MSM fixture-assisted magnetization strategy; (c2) final structure of the MSM. (d) Dual-mode composite application scenario of the MSM within a blood vessel

2.2 Fabrication process and magnetization strategy

The fabrication process of the MSM is illustrated in Fig. 1b, which involved the following key steps. First, the PDMS, curing agent, and NdFeB powder were mixed at a mass ratio of 10:1:10 and thoroughly homogenized using a magnetic stirrer for 10 min, followed by vacuum degassing of the mixture at -95 kPa for 5 min. After degassing, the mixture was cast into a high-precision, stereolithography three-dimensional (3D)-printed sacrificial mold. The mold filled

with the PDMS-magnetic particle composite was then placed on an 85°C hotplate for 2.5 h to achieve thermal curing. The mold was fabricated from a high-temperature-resistant resin to maintain structural stability during heating, thereby ensuring the preservation of the intended microrobot geometry. After complete curing, the assembly was immersed in acetone for 10 min to dissolve and embrittle the sacrificial mold, allowing it to be mechanically peeled away from the internal MSM structure. Finally, the feeder channels, which served as inlets for the composite material during casting, were carefully excised to release the flexible main body of the microrobot

(Fig. 1b1). Scanning electron microscopy (SEM; GeminiSEM 300, Zeiss, Inc., Oberkochen, Germany) characterization revealed that in the cross-sectional morphology of MSM, NdFeB magnetic particles were uniformly dispersed within the PDMS matrix (Fig. 1b2).

The preset magnetization profile was imparted by placing the molded microrobot into a custom-made magnetization-assist fixture and applying a 3-T pulsed magnetic field. The resulting magnetization orientation is depicted in Fig. 1c1. To ensure synchronous rotation of the two helical ends about the central axis under an oscillatory magnetic field, both ends were designed with identical radial magnetization directions. An angular misalignment between the magnetic moments of the two ends would introduce a phase lag during helical motion, generating torque on the central segment and thereby compromising the overall propulsion efficiency. To realize the oscillatory motion mode, the central segment was programmed with a bidirectional axial magnetization pattern with a 2:1 length ratio, where the longer axially magnetized region is defined as the head and the shorter one as the tail. The final architecture of the MSM is shown in Fig. 1c2, featuring a total length of 15 mm, with both helical ends measuring 3 mm in length and 1 mm in diameter.

2.3 Driving strategy

To drive the MSM, this study employed a custom-developed mechano-electromagnetic hybrid actuation system consisting of an actuation module, a computer, a programmable current source (APS-1102A, GW Instek, Suzhou, China), a motion controller, and a charge-coupled device camera (Sony XCD-SX90, Tokyo, Japan). The actuation module included a set of Helmholtz coils and a motorized rotary stage (Y200RA400, Beijing Jiangyun Photoelectric Equipment Co., Ltd., Beijing, China) [40]. The coils generated tunable magnetic fields with an intensity range of 15–27 mT that controlled the motion modes of the MSM, while the motorized rotary stage adjusted the magnetic field direction to steer its trajectory. By integrating the rotary stage with the electromagnetic coils, a rotating magnetic field could be generated within the plane. Furthermore, applying an alternating current to the coils via the programmable power supply produced an oscillatory magnetic field along the coil axis with tunable frequency. As shown in Fig. 1d, seamless switching between the oscillatory and helical motion modes of the MSM was achieved solely by adjusting the magnetic field oscillation frequency. Under a low-frequency oscillatory field, the MSM exhibited a C-shaped reciprocating motion that is suitable for rapid propulsion in open environments and adaptation to uneven terrain. In contrast, under a high-frequency oscillatory field, the MSM approximated a linear shape and rotated around its axis, enabling propulsion via interaction between its helical structure and the surrounding fluid, enabling navigation within confined channels.

3 Results and discussion

3.1 Locomotion performance and mode switching of the MSM

Motion images of the two motion modes achieved by the MSM under magnetic field control are shown in Fig. 2a (Movie S1 in the supplementary information). The oscillatory mode (Fig. 2a1) was performed in an open environment, while the helical mode (Fig. 2a2) was conducted inside a transparent silicone tube with an inner diameter of 2 mm. To characterize the locomotion performance of the MSM, we investigated the relationship between its velocity and the oscillation frequency under various magnetic field intensities. All experiments were performed in a glycerol–water mixture (volume ratio of 2:3) to simulate blood viscosity. To validate the universality of the experimental results, three dual-mode microrobots with lengths of 15, 20, and 25 mm, respectively, were fabricated. To ensure the reliability of the experimental results, five parallel samples of MSM were prepared for each dimensional specification in all subsequent locomotion performance tests.

The motion behavior of the MSM across different oscillation frequencies could be divided into four distinct stages, as illustrated in Figs. 2b, 2e, and 2h.

Stage I (oscillatory mode): The microrobot is characterized by an overall distinct C-shaped deformation. In this stage, the magnetic field oscillation frequency is low, the helical structures at both ends do not rotate, and locomotion is primarily driven by the reciprocating oscillation of the middle section. Owing to the 2:1 axial magnetization ratio of the middle section, we defined the longer segment as the head and the shorter one as the tail. Under low-frequency excitation, the head possesses a larger magnetic moment and exhibits a stronger oscillation amplitude, generating greater propulsive force than the tail, thus causing the MSM to move head-first. This behavior corresponds to the oscillatory mode depicted in Fig. 2a1 and the rising trend of the oscillatory velocity shown in Figs. 2c, 2f, and 2i.

Stage II (hybrid mode): The oscillatory and helical behaviors of the microrobot occur at the same time. When the magnetic field oscillation frequency exceeds a critical threshold, i.e., the minimum frequency at which the middle elastic segment of the MSM loses synchronous response to magnetic excitation, the middle segment enters a jumping state and can no longer track the rapid directional changes of the magnetic field. Although the oscillatory motion weakens, it does not completely vanish. Simultaneously, unstable helical motion begins to emerge at both ends, imparting some lateral displacement to the overall structure. This transitional stage manifests as a decline in oscillatory velocity, as shown in Figs. 2c, 2f, and 2i.

Stage III (helical mode): Here, the middle section becomes completely out-of-step with the magnetic field and ceases to

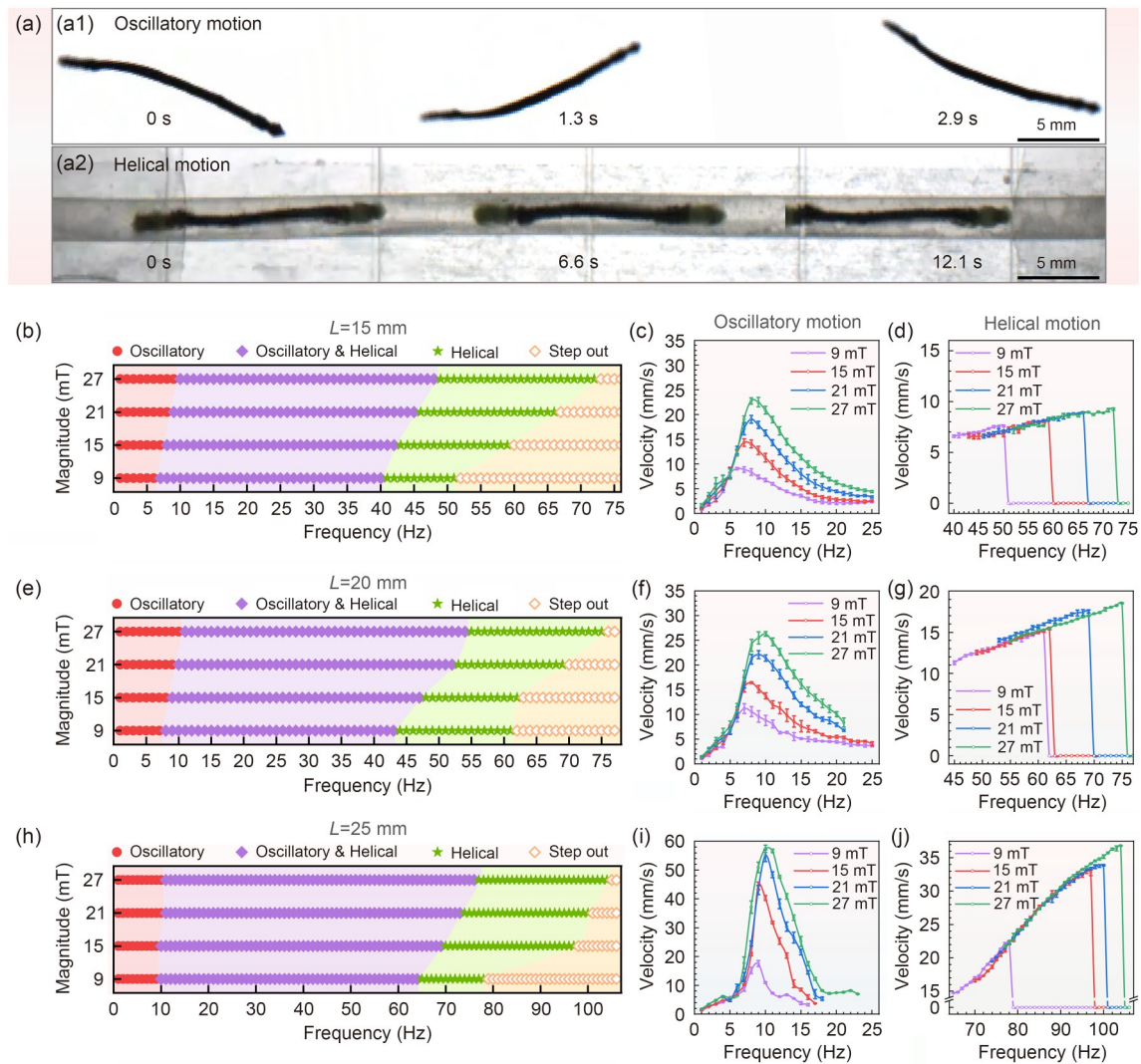


Fig. 2 Switching between the two motion modes of the mode-switchable microrobot (MSM). (a) Experimentally observed dual-mode motion of the MSM: (a1) oscillatory motion mode of the MSM; (a2) helical motion mode of the MSM. (b–d) Motion mode of the 15-mm MSM and the velocities of its oscillatory and helical modes as a function of magnetic field frequency and strength. (e–g) 20-mm MSM. (h–j) 25-mm MSM. Data in (c, d, f, g, i, j) are based on $n=5$ independent experiments

contribute to propulsion, whereas stable and continuous helical rotation is established at both ends, driving the MSM linearly along its axis. As shown in Figs. 2d, 2g, and 2j, the propulsion velocity in this mode increases approximately linearly with frequency.

Stage IV (out-of-step): The MSM exhibits no effective motion, corresponding to the regions in Figs. 2d, 2g, and 2j, where the helical velocity drops to zero.

The quantitative results revealed that the locomotion velocity scales with the MSM size in both modes. The maximum oscillatory velocities for the 15-, 20-, and 25-mm MSMs were 23, 27, and 57 mm/s, respectively. Correspondingly, their maximum helical velocities were 9.2, 18.5, and 36.8 mm/s. This demonstrates that the locomotion velocity increased with size in both modes. Within each length group, the oscillatory velocity initially increased and then decreased with rising

frequency, and at any given frequency, a higher magnetic field intensity resulted in a greater velocity. In contrast, the helical velocity increased approximately linearly with frequency and was relatively insensitive to changes in magnetic field intensity, with velocity fluctuations around ± 0.5 mm/s. Further analysis revealed that, for any given length, the frequency ranges corresponding to the oscillatory mode and the helical mode did not overlap, confirming that motion mode switching can be achieved solely through frequency modulation. The MSM combined the locomotion characteristics of fish-like microrobots and helical microrobots, exhibiting similar velocity trends. Owing to the distinct frequency responses of the two modes, the MSM can adapt to complex environments with different spatial constraints by adjusting the magnetic field oscillation frequency. While the 20- and 25-mm MSMs exhibit higher locomotion velocities, the 15-mm MSM

achieves an optimal balance between locomotion performance and spatial adaptability, which is the main consideration for its selection as the research object. Such superior environmental compatibility and maneuverability align with the study's core research orientation of developing microrobots for practical in vivo targeted locomotion and drug delivery applications, where spatial accessibility and adaptive motion are prioritized over pure velocity performance.

It is noteworthy that during helical motion, there was a probability of tail-led motion, wherein the rotational direction of the two helical ends was opposite to that observed in head-first propulsion. In such cases, briefly deactivating and reactivating the magnetic field could reverse the rotation direction and restore forward motion capability. Although this bidirectionality presented a minor limitation in the current study, it also revealed a potential advantage: the helical mode inherently supports bidirectional locomotion. Therefore, when the MSM enters a dead end or an unintended path, this feature can be utilized for autonomous directional correction. For a more comprehensive illustration of the performance merits of the proposed MSM, a detailed comparison with representative multimodal magnetic microrobots is presented in Table S1 and Fig. S1 (supplementary information), which underscores the advantageous features of the MSM in frequency-mediated mode switching and adaptability to biomedical environments.

3.2 Validation of MSM locomotion adaptation in unstructured environments

The experimental results presented in Sect. 3.1 have demonstrated that the motion mode of the MSM can be switched solely by modulating the oscillation frequency of the magnetic field, with both the oscillatory and helical modes exhibiting high locomotion efficiency. The relationship between magnetic field parameters and MSM velocity, established through performance validation, provides a basis for selecting appropriate field parameters in different application scenarios. However, it should be noted that all the above experiments were conducted in flat laboratory dishes, whereas practical application environments (e.g., biological tissues) often involve unstructured terrains characterized by undulating paths and irregular wall surfaces. Therefore, to advance the biomedical applications of the MSM, it is essential to evaluate its adaptability under non-ideal conditions.

First, we evaluated the slope-climbing capability of the MSM in oscillatory mode. Six supporting bases with different inclination angles were fabricated using 3D printing. A cylindrical container was fixed onto these bases and filled with a glycerol–water mixture (volume ratio 2:3). The MSM was placed at the bottom of the container and driven upward under four different magnetic field intensities (with the oscillation frequency fixed at 5 Hz). As shown in Figs. 3a–3f,

under a 9-mT magnetic field, the MSM could only overcome a slope of 15°. In contrast, under a 27-mT field, the MSM was able to move fully upward against gravity in the vertical container (90°).

We further constructed a vascular model with variable diameters and arched slopes to assess the motion ability of the MSM in more complex environments (Figs. 3g and 3h). The performance of the MSM in traversing this model was compared between its oscillatory (5 Hz) and helical (55 Hz) modes under a 27-mT field. The oscillatory mode accomplished the task in merely 3 s, significantly faster than the 9.5 s required in the helical mode (Movie S2 in the supplementary information). Therefore, considering both locomotion efficiency and control simplicity, it is advisable to employ the oscillatory mode from the initial stage for rapid slope traversal.

Furthermore, in certain biological environments, fluid does not fully fill the lumen but rather adheres to the wall in the form of a mucous layer. To simulate such conditions, a segment of porcine trachea with folded inner walls was used, and a small amount of glycerol solution was added to mimic pulmonary fluid retention. The experimental results confirmed that the MSM could still propel forward in oscillatory mode in this fluid-limited environment, and the folded structure of the tracheal wall did not significantly impede its motion (Fig. 3i).

The slope-climbing tests, variable-diameter arched vascular model traversal experiments, and ex vivo porcine trachea validation tests demonstrated that the MSM exhibited effective slope-climbing capability, achieved passive simple 3D motion in unstructured environments, and performed intended locomotion tasks under conditions closely resembling real biomedical settings.

3.3 Directional locomotion and targeted drug delivery of the MSM in a vascular model

To fully demonstrate the locomotion performance of the MSM and the application potential of its mode switching, this study further conducted a path-following demonstration inside a 3D-printed vascular model. The model featured a square outline with a side length of 9 cm and an inner diameter ranging from 3 mm to 6 mm. An MSM with a length of 15 mm was employed to perform multimodal locomotion and targeted drug delivery verification within this transparent resin-based vascular structure. Using a mechanical-electromagnetic hybrid drive system, the MSM was navigated through the vascular model filled with glycerol solution via motion mode switching.

To simulate the flow rate in venous blood vessels, the right opening of the vascular model was connected to a microfluidic pump syringe, which injected glycerol solution mixed with red ink at a flow rate of 1 mL/min for clear visualization of the fluid. Meanwhile, the left opening was connected to a collection bottle to recover the outflow. The motion sequence of the MSM inside the vascular model is shown in

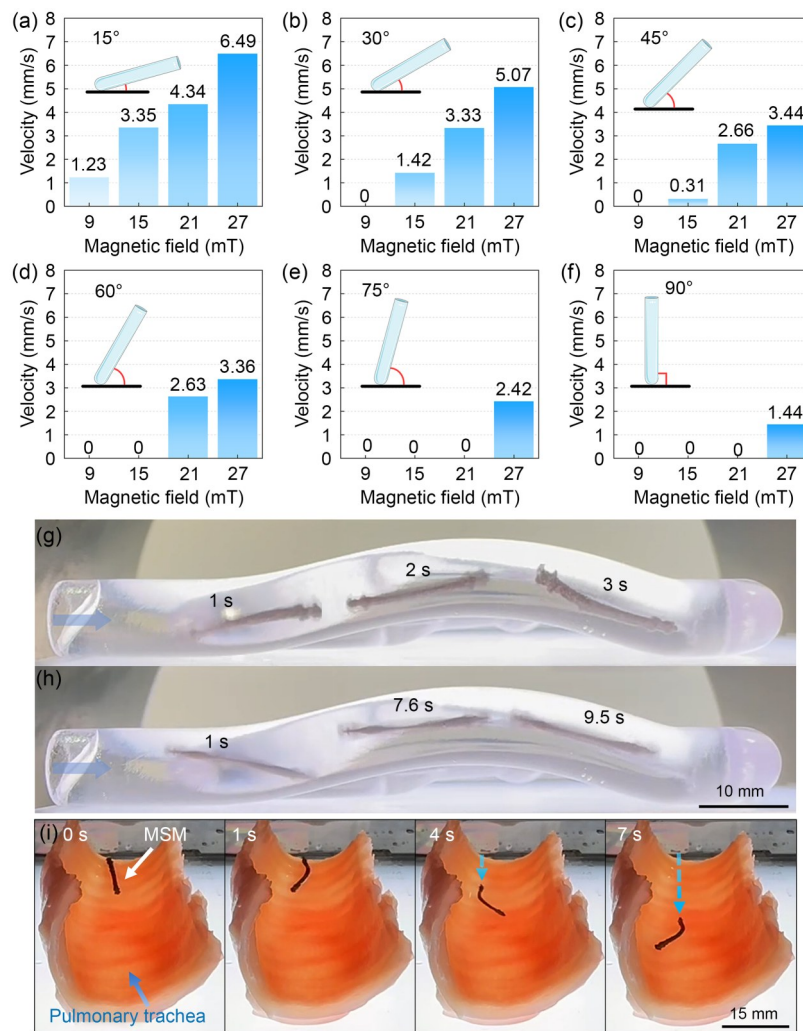


Fig. 3 Motion adaptability of the mode-switchable microrobot (MSM). (a–f) Climbing performance of the MSM in oscillatory mode under various magnetic fields. (g, h) Motion of the MSM through a vaulted model in oscillatory (g) and helical (h) modes. (i) The MSM exhibits oscillatory movement within an ex vivo porcine trachea

Fig. 4a. Initially, under an oscillatory magnetic field of 27 mT and 5 Hz, the MSM moved in oscillatory mode, traversing the initial slope and completing a turn. The magnetic field frequency was then adjusted to 55 Hz, switching the MSM to helical mode to enter the first narrow segment. After passing this segment, the frequency was reset to 5 Hz, and combined with coil rotation, the MSM entered a bypass in oscillatory mode. Upon reaching the second narrow segment, the frequency was again set to 55 Hz. After traversal, the frequency was switched back to 5 Hz, guiding the MSM along an inverted Z-shaped path out of the bypass, eventually reaching the right opening of the model (Movie S3 in the supplementary information).

It should be noted that when the MSM passed through the first narrow segment, its velocity decreased due to the reduced cross-sectional area. As its head entered the constriction, a sudden increase in flow velocity caused a temporary backward push on the MSM. In this situation, simply adjusting

the magnetic field frequency enabled it to re-engage in helical mode and continue forward movement.

In the design of the MSM, surface coating was adopted for drug loading. To ensure stable drug adhesion in a liquid environment and achieve controlled release, GelMA was selected as the drug carrier, which exhibits excellent structural and performance stability at physiological temperature ($\approx 37^\circ\text{C}$) [41]. Red ink was mixed into the GelMA to simulate the drug, and release was triggered by localized heating. This carrier can reliably deliver the drug to the target site at physiological temperature and release it efficiently at a slightly elevated temperature (40°C), while ensuring that the release process is harmless to biological tissues [42]. The experiment was conducted in glycerol solution flowing at 1 mL/min. After driving the drug-loaded MSM to the target location, an NIR heating lamp was activated and set to 40°C . The drug release result was observed after approximately 10 min, as illustrated in Fig. 4b (Movie S4 in the



Fig. 4 Locomotion and drug delivery of microrobots in the model. (a) The mode-switchable microrobot (MSM) traverses the vascular model by employing a dual-mode locomotion mechanism. (b) The MSM achieves drug release upon near-infrared irradiation, heating to 40 °C in a vascular model

supplementary information). This demonstrated that the MSM can remain stationed under low flow conditions due to gravity, and the released drug can accumulate at the target site.

3.4 Directional navigation of MSM in ex vivo organs

To validate the motion and steering performance of the MSM in an environment approximating real physiological conditions, we further conducted experiments in ex vivo organs. An intact porcine bronchial tree was selected as the locomotion environment for the MSM. A small amount of glycerol solution was introduced to simulate pulmonary fluid retention, thereby enabling the assessment of the dual-mode motion adaptability and path-correction capability of the MSM in a complex setting, as illustrated in Fig. 5a. During the experiment, the MSM was placed at the main bronchus with a maximum diameter of 19.5 mm, with the target location set as the left outlet of the upper branch, as illustrated in Fig. 5b (Movie S5 in the supplementary information). In Fig. 5b, the blue dashed line outlines the bronchial structure, the yellow rectangles indicate the MSM operating in oscillatory mode with an average velocity of 7.2 mm/s (standard deviation: ± 0.6 mm/s), and the yellow ellipses indicate helical mode with an average velocity of 3.8 mm/s (standard deviation: ± 0.2 mm/s). The blue solid line represents the trajectory under oscillatory mode, while the green solid line corresponds

to helical mode. Given the relatively large diameter of the main bronchus, the initial magnetic field was set to 27 mT with an oscillation frequency of 5 Hz to drive the MSM in oscillatory mode. When the MSM advanced to the bronchial segment narrowed to 5 mm in diameter, the oscillation frequency was adjusted to 55 Hz to switch its motion mode to helical motion, which was sustained until the MSM reached the distal bronchial outlet with the narrowest diameter of 3 mm. When the MSM reached the first bifurcation, a clockwise rotating magnetic field was applied to guide it into the upper branch, and the field was then switched to counterclockwise rotation to sustain motion along this branch. Between 10 and 11 s, the MSM reached the final bifurcation but erroneously entered the upper outlet, preventing further advance. Utilizing the helical mode, it successfully exited the upper outlet by 13 s. After deactivating and reactivating the magnetic field, the MSM continued forward in helical mode under a counterclockwise rotating field until it reached the left opening of the upper branch. This experiment demonstrated that the MSM can autonomously adjust its motion mode in response to environmental width variations and utilize helical motion to correct undesired paths and return to the intended route.

After the validation of MSM motion and targeted drug delivery within a vascular model, this study further selected a segment of porcine liver vein to conduct targeted drug delivery experiments (Fig. 5c). Due to the low optical transparency

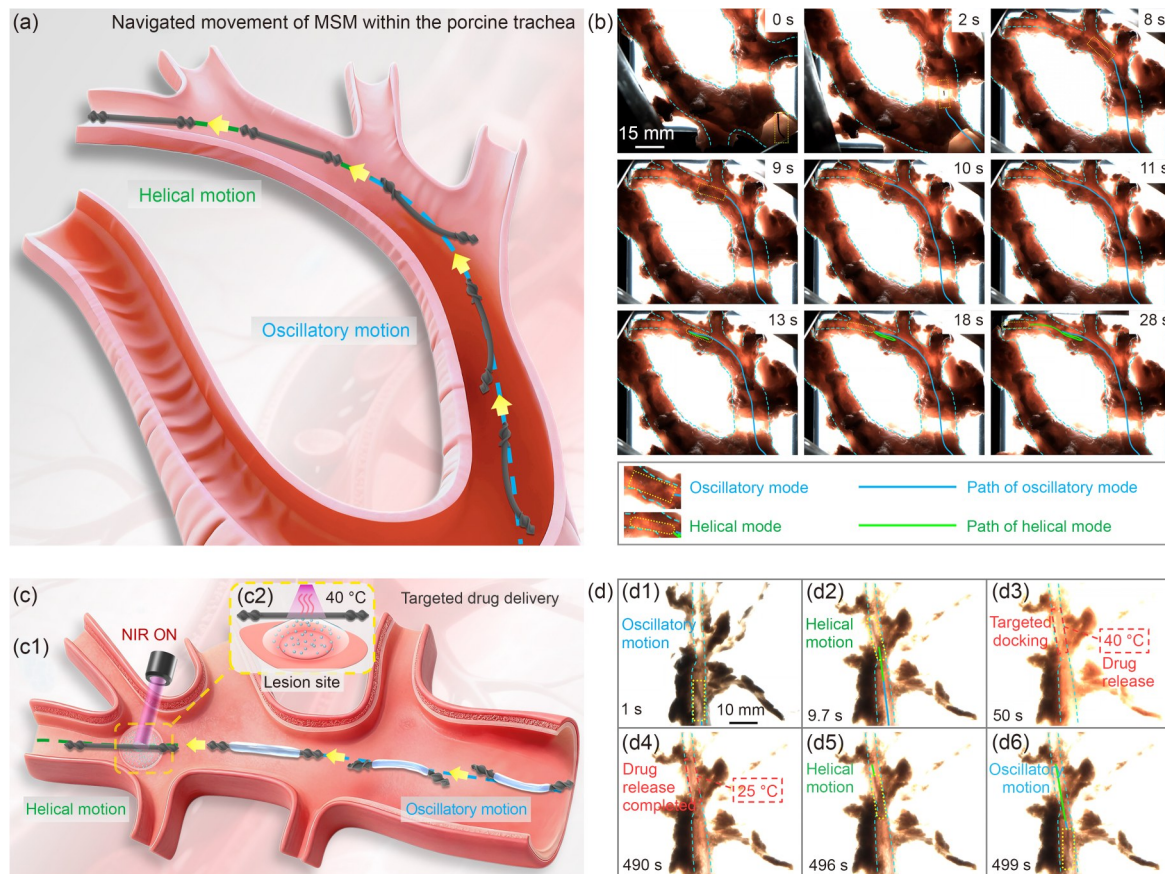


Fig. 5 Investigation of mode-switchable microrobot (MSM) functions in ex vivo organs. (a) Schematic diagram of MSM movement within the porcine trachea. (b) Movement and mode switching of MSM in an ex vivo porcine trachea. (c) Schematic diagram of MSM movement and drug release within porcine liver veins: (c1) locomotion of drug-loaded MSM within porcine liver veins; (c2) drug release by the MSM at the target site within the porcine liver vein. (d) MSM movement with drug release in an ex vivo porcine liver vein

of the venous tissue, backlight imaging with high exposure parameters was used to identify the posture of the MSM from its shadow. To simulate blood viscosity, a glycerol solution was injected into the vein. For intravascular targeted drug delivery tests, a 0.5-mm-thick layer of GelMA hydrogel mixed with red ink was coated on the middle section of the MSM (Fig. 5c2). The MSM was placed at one end of the vein, and a mode-switching test was first performed to probe variations in the internal venous width. In Fig. 5d, the blue dashed line indicates the inner wall of the porcine liver vein, the yellow dashed line outlines the MSM, the solid blue line segment represents its oscillating motion trajectory, and the solid green line segment represents its helical motion trajectory. Initially, under a magnetic field of 27 mT and an oscillation frequency of 5 Hz, the MSM moved forward in oscillatory mode within the venous segment with a diameter of approximately 6.1 mm (Fig. 5d1). When it reached a narrow segment with a diameter of 4.6 mm in the mid-section of the vein (Fig. 5d2), the oscillatory mode could not sustain forward progress. The oscillation frequency was then adjusted to 55 Hz, causing the MSM to transition to helical mode and successfully advance to the opposite end of the vein.

Once the drug-loaded MSM was driven to the target site within the vein and immobilized, an NIR heating lamp was activated and set to an irradiation temperature of 40 °C to initiate drug release (Fig. 5d3). After continuous irradiation for approximately 8 min, the NIR lamp was turned off, completing the drug release process (Fig. 5d4). Upon reapplication of the magnetic field, the MSM moved toward the lower end of the vein in helical mode (Fig. 5d5), switched back to oscillatory mode upon reaching an open region, and ultimately returned to its starting position (Fig. 5d6; Movie S6 in the supplementary information). These results confirm that the MSM exhibits excellent environmental adaptability and controllable locomotion in complex ex vivo biological tissues, demonstrating its potential to perform targeted tasks under realistic physiological conditions.

4 Conclusions

This study successfully designed and fabricated a magnetically driven soft microrobot with dual-mode locomotion capability, which can achieve seamless switching between

oscillatory and helical modes under oscillatory magnetic fields of different frequencies. The precisely programmed magnetization and structural geometry of the microrobot enable a C-shaped oscillatory motion at low frequencies for rapid traversal of open and unstructured environments, and a helical rotation at high frequencies for stable navigation within confined fluidic channels. The two modes operate in discrete, non-overlapping frequency bands, ensuring rapid and reliable mode switching through simple frequency modulation and resulting in exceptional locomotion controllability.

Beyond efficient motion in simple environments, the MSM demonstrated remarkable environmental adaptability by successfully completing complex path-following and navigation tasks in biomimetic vascular models. Experiments in ex vivo tissues (porcine trachea and liver veins) further validated its capability for multi-path navigation and direction correction. Moreover, the integration of a photothermal-responsive GelMA drug carrier enabled targeted drug delivery and on-demand localized release via NIR irradiation.

In summary, the MSM and control strategy proposed in this work expand the locomotion capabilities of soft microrobots in complex environments. Furthermore, they provide a feasible technological foundation and experimental basis for future practical applications in biomedical fields such as minimally invasive surgery, targeted drug delivery, and in vivo diagnostics. This design is also feasible for scaling to sub-millimeter and microscale dimensions via high-precision microfabrication of magneto-soft structures. Meanwhile, key challenges remain in maintaining adequate magnetic actuation force and achieving precise microscale motion control in viscous biological media.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1631/bdm.2600013>.

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Author contributions HY, DQX, LSZ, and QHG proposed the original idea and planned the configuration. DQX, QHG, LSZ, YXL, and DTS completed the experiments, software, and data curation. QHG and LSZ wrote the manuscript. HY, LSZ, HZ, NDJ, and LNS revised the paper for language and quality. All authors have read and agreed to the published version of the manuscript.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human or animal subjects performed by any of the authors.

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

Use of generative AI tools During the preparation of this work, the authors utilized DeepSeek to refine the manuscript's linguistic quality and ensure grammatical precision. Subsequently, the authors critically reviewed, revised, and edited the content to ensure it met scholarly standards and maintained academic integrity. The authors take full responsibility for the final content of the publication.

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