

Supplementary information for

Qinghao Guo, Liushuai Zheng, Dongqin Xu, Yixin Liu, Dingtong Shen, Hao Zhang, Niandong Jiao, Lining Sun, Hao Yang, 2026. Magnetic frequency-controlled mode-switchable flexible microrobot enabling adaptive locomotion in biological channels for targeted drug delivery. *Bio-Des Manuf*, 9(5):814-824. <https://doi.org/10.1631/bdm.2600013>

1. MSM and other multimodal magnetic microrobots performance index

We systematically compare the performance of the proposed MSM with those of representative multimodal magnetic microrobots reported in recent years. To ensure the comprehensiveness and objectivity of the comparison, we comprehensively evaluate and quantitatively score the performance of various microrobots from six core dimensions: motion efficiency, motion accuracy, environmental adaptability, functionality, flexibility, and ease of control. The scoring criteria are mainly based on the original experimental data provided in the published papers and supplementary materials of the corresponding studies. All raw data of the compared microrobots have been summarized and organized in Table S1. On this basis, we rank and score the performance of each type of microrobot in the above dimensions, with a scoring range of 0–10; a higher score indicates a more significant performance advantage in the corresponding dimension. Finally, based on the scores of each dimension, a performance radar chart of multimodal magnetic microrobots is plotted (Fig. S1), which intuitively presents the performance differences and advantageous characteristics of various microrobots.

Table S1. The original data of microrobot indicators

	Motion efficiency	Motion accuracy	Environmental adaptability	Functionality	Flexibility	Ease of control
MSM	Max. 57 mm/s (oscillation mode), max. 36.8 mm/s (spiral mode)	Dual modes: oscillation and spiral (switched by frequency)	Simulated blood vessels/ex vivo organs, 90° vertical movement	Targeted drug delivery, path correction	Rapid mode switching, 3 sizes for adaptation	Magnetic frequency/intensity control, visual closed-loop
MSPM [1]	Max. 122.7 mm/s (ground), max. 34.9 mm/s (underwater)	Triple modes: rolling, flipping, propulsion (switched by magnetic direction)	3D maze, tubular fluid environment, driven by 2 mT low magnetic field	Directional transport of fluids/particles, path following	Adaptive switching of ground modes	PID closed-loop, cable-free remote control
STFM-Robot [2]	Driven by 2 mT low magnetic field, mode efficiency adapted to scenarios	Four modes: undulatory, rolling, flipping, spiral	1 mm narrow channel, ex vivo porcine intestinal cavity, pH/ion self-adaptation	Cell/drug delivery, biodegradable	Reversible shape switching (0°–180°)	Knowledge graph mapping, PID closed-loop
Wheel-leg [3]	Wheel mode more efficient than leg mode, optimized by variable pitch angle in liquid	Dual modes: leg walking, wheel rolling (triggered by temperature and humidity)	2 mm narrow channel, 30° slope, amphibious environment	Micro-target capture and transport (load 13 times its own weight)	Coordinated switching of shape and mode	Magnetic type/frequency control, hierarchical closed-loop
Pose-aware [4]	Optimal efficiency at 38 mT, reprogramming cycle 30 s	Four modes: swimming, rolling, crawling, obstacle surmounting	Gastrointestinal environment, pose sensing (± 3 mm/ $\pm 2.5^\circ$)	Targeted delivery, potential for tissue biopsy	Segmented magnetization reprogramming, rapid mode switching	Three-magnetic-field modular control, RFID positioning

MMMR [5]	Spiral swimming linearly related to frequency, driven by 8 mT	Dual modes: spiral swimming, bipedal walking	Physiological lumen, 30° slope, amphibious environment	Drug delivery, navigation and recovery in artificial bladder model	Mode switching without structural change	PID closed-loop control of height and direction
MFMLS robot [6]	Efficient movement below 100 mT, no attenuation after cycles	Multi-modes: curling, rolling, crawling, etc.	Resistant to acid-base/body fluid/ultrasound, biocompatible	Environmental sensing, circuit repair, gastric ulcer treatment	Customizable magnetization programming, replaceable modules	Magnetic direction/intensity control, easy operation
FHMR [7]	Max. 3 mm/s, positively related to frequency, mode-specific critical frequency	Five modes (driven by magnetization orientation, magnetic field type)	Micro-millimeter scale lumen, high-viscosity liquid	Thrombus removal, drug delivery (encapsulation rate >60%)	Customizable structure size, flexible mode combination	Eight-coil control, PID closed-loop (error ≈ 0.5 mm)

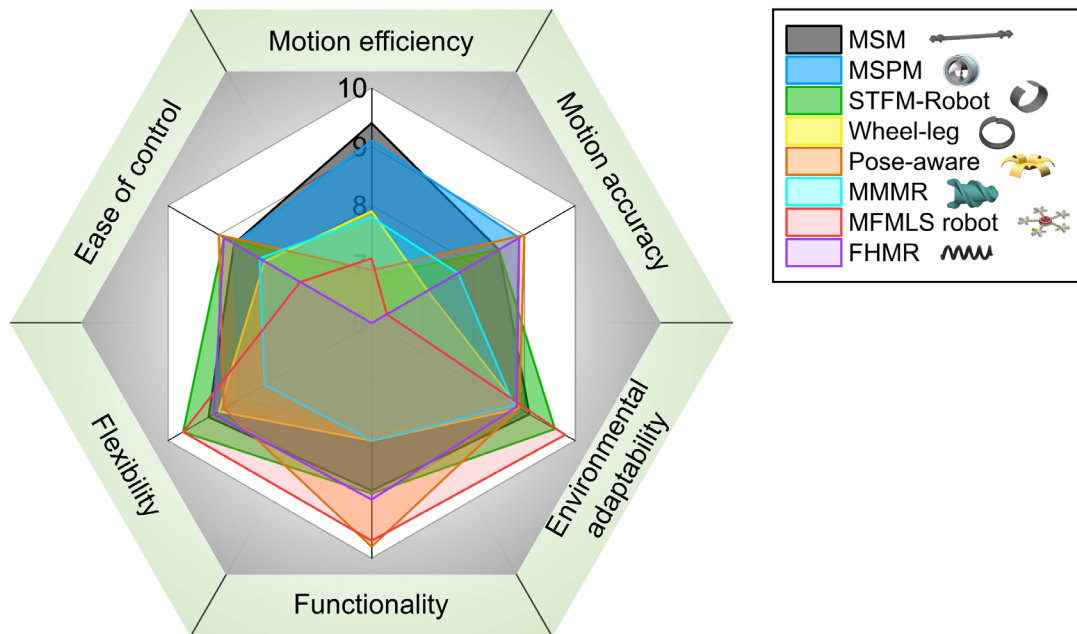


Fig. S1 Comparison between MSM and other multimodal magnetic microrobots. Comparison from the aspects of motion efficiency, motion accuracy, environmental adaptability, functionality, flexibility, and ease of control between MSM and MSPM [1], STFM-Robot [2], Wheel-leg [3], Pose-aware [4], MMMR [5], MFMLS robot [6], and FHMR [7].

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2. Description of video content

Movie S1.

Oscillatory and helical dual-mode motion of the MSM

Movie S2.

Slope climbing test of the MSM in oscillatory and helical modes

Movie S3.

The MSM traverses the vascular model by employing a dual-mode locomotion mechanism

Movie S4.

Drug release by MSM within a vascular model

Movie S5.

Movement of MSM within the porcine trachea

Movie S6.

Movement of MSM within porcine hepatic veins enabling targeted drug delivery