

Using Magnetorheological Fluid to Enable a Rolling-Actuated Soft Robot for Tissue-Sparing, Magnetically Controlled, Minimally Invasive Therapy

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Abstract. To address the limitations of rigid traditional endoscopes and interventional tools in narrow, fragile anatomical pathways, this project proposes an innovative soft robotic concept based on magnetorheological fluid (MRF). Enclosed within a flexible cavity, the MRF is driven wirelessly by spatial magnetic field gradients generated by an external electromagnetic array. This field induces coordinated deformation and a non-contact rolling motion, fundamentally minimizing luminal shear stress compared to conventional sliding systems. In this work, the physical relationship between the driving torque and magnetic field gradient is mathematically modeled and verified via comprehensive multi-physics COMSOL simulations. For experimental validation, a physical proof-of-concept platform was developed to evaluate performance in simulated gastrointestinal and vascular interventions. Physical testing confirms that the rolling MRF robot achieves stable straight-line locomotion with a 92% success rate, exhibits sub-millimeter targeted positioning accuracy (0.51 mm), withstands heavy fluidic drag up to 25 L/min flow velocities, and achieves a transport load capacity of up to 4.5 N. Most crucially, biomechanical evaluation verifies that transitioning from sliding to rolling locomotion reduces cumulative tissue friction impulse by approximately 96%. This technology offers a safer, highly compliant, ultra-minimally invasive interventional strategy for advanced target drug delivery and endovascular thrombus clearance.

Keywords: Magnetorheological Fluid, Soft robots, Magnetic actuation, Electromagnet, Arduino

1. Background research

Globally, diseases in the body's major tubular systems, the cardiovascular system and digestive system, hold an enormous share of deaths annually. These metrics added together account for ~21.92 million deaths and ~32% of all global deaths annually [1]. Despite these huge death counts for these types of diseases, current therapeutic approaches still face limitations in invasiveness, precision, response speed, and tissue safety.

Button Battery Ingestion: Button battery ingestion is a clinically important emergency in children, and current removal strategies may still cause complications when tissue injury has already

occurred [2, 3].

Foreign Object Removal (Digestive Tract): Endoscopic or surgical removal can be helpful, but it's invasive, very skill-based, resource-heavy and has a high chance of trauma, especially when tissue is already injured [2, 3].

Blood Clot Formation: Every year, 1 in 4 people worldwide die from conditions related to thrombosis [1]. This is the root cause of many cardiovascular killers, including stroke, heart attack, and VTE. Currently, we have anticoagulants (blood thinners) as our main solution. But there are two main problems with them: they aren't very fast-acting (minimum a few minutes to take effect), and contrary to popular belief, blood thinners don't immediately dissolve blood clots; they only stop new clots from growing, therefore giving time for the body to SLOWLY dissolve the preexisting blood clot.

2. Motivation

Growing up in Canada, my summers in China felt like a second home, with family dinners, then card games with my grandmother and her sister. Three years ago, that routine ended when my Grandma suffered a sudden stroke. Treatment via anticoagulants arrived in time, but it triggered a severe intracerebral hemorrhage, and she has been bedridden ever since. Watching her recovery made one thing painfully clear: for many patients, getting help to the right place at the right time inside the body is still hard.

Modern endoscopes and catheter-based tools save lives, but they can be rigid, limited in their ability to navigate tight or delicate anatomy, and sometimes risk irritating or damaging tissue, especially in long, narrow, curved pathways such as blood vessels and parts of the digestive tract. In my mind, the problem wasn't just "make tools smaller." It was "make them softer, safer, and more controllable in confined spaces."

3. Background

3.1. Soft robots

To address these problems, soft robotics has emerged as a cutting-edge, promising field for many scientists [4]. However, many existing soft robots still face practical limits, such as complex structures, difficult control, or insufficient stability and precision in real tubular environments. Actuation is essentially the method a robot uses to move [5, 6]. Main methods include:

- Hydraulic: Water-controlled
- Electric: Electrorheological fluids, dielectric elastomers
- Stimuli-Responsive: Light, Thermo
- Cable-Tendon Driven: Similar to traditional robotics
- Magnetic: Magnetic Elastomers, Magnetorheological fluids

In medical tubing, many of these approaches require tethers or internal hardware that adds friction and increases injury risk. For in-vivo motion, the key requirement becomes: wireless actuation with precise control.

3.2. Magnetic actuation & magnetorheological fluid

Magnetic control is promising because it enables tether-free operation, reducing mechanical drag and friction on internal tissues. There are two main types: Magnetic Elastomers (properties are fixed

once fabricated) and Magnetorheological fluids (MRFs) [7].

MRFs are suspensions of magnetizable particles. Without a magnetic field, the MRF has low viscosity, but once exposed to one, the particles form a chain-like structure (Figure 1), enabling them to drastically change their resistance to flow (yield stress) and shift toward a solid-like state within milliseconds [8-10].

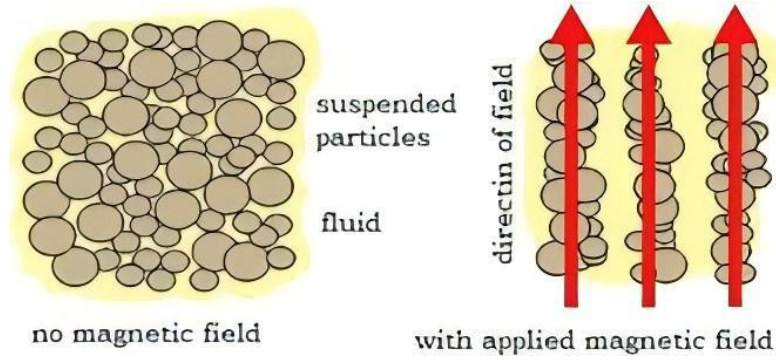


Figure 1. MRF particle orientation with and without an applied magnetic field

The MRF in "off" mode follows the Newtonian Model:

$$\tau = \eta_0 \dot{\gamma} \quad (1)$$

The MRF in "on" mode follows the Bingham Plastic Model:

$$\tau(H, \dot{\gamma}) = \begin{cases} G\dot{\gamma}, & |\tau| < \tau_y(H) \quad (\text{Pre - yield : solid - like}) \\ \tau_y(H) \text{sgn}(\dot{\gamma}) + \eta_p \dot{\gamma}, & |\tau| \geq \tau_y(H) \quad (\text{Post - yield : flow}) \end{cases} \quad (2)$$

As shown in Figure 2, the yield stress and viscosity of MRF are strongly dependent on the applied magnetic field strength – without a field, the fluid behaves as a low-viscosity Newtonian liquid; under moderate to large fields, it develops a significant yield stress and rapidly transitions to a solid-like state, providing controllable flow resistance.

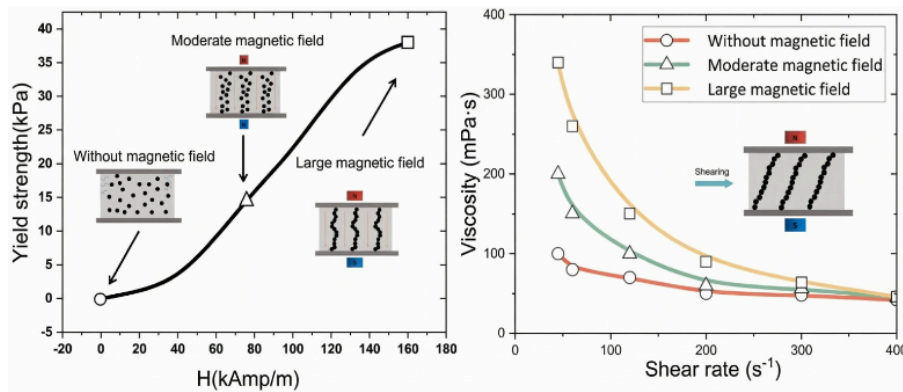


Figure 2. Magnetic field control of yield strength and viscosity in magnetorheological materia

Currently, MRFs are underused as a core actuation mechanism in soft robotics due to the potential impact of sliding friction generated during motion on biological tissues [11-13]. That is why we are designing a rolling version of the magnetorheological fluid.

3.3. Research gap & hypothesis

Most existing tubular robots rely on sliding locomotion, which increases friction and shear. The key research gap is the lack of an established approach using MRF to produce rolling locomotion within confined tubular environments.

Hypothesis: If a soft robot is constructed using magnetorheological fluid and actuated by dynamically controlled magnetic fields, it will achieve rolling locomotion, enabling tissue-sparing, high-flexibility minimally invasive therapy.

As shown in Figure 3, the research framework systematically guides the investigation from theoretical modeling to experimental validation.

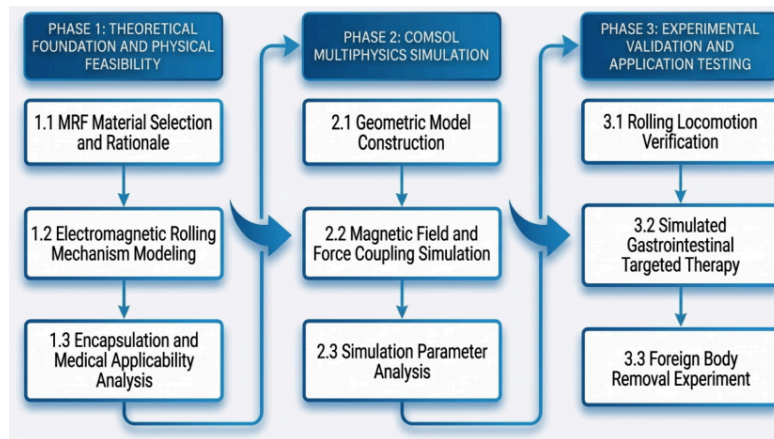


Figure 3. Research framework

4. Phase 1: foundational physics

Electromagnets were selected as the field source because they are switchable and tunable, enabling time-sequenced current control [14, 15]. A net body force arises from the field gradient, and particle chains realign to generate torque. As shown in Figure 4, this schematic illustrates the transition from particle-level chain alignment to the macroscopic performance evolution, including the induced off-centre force and rolling torque.

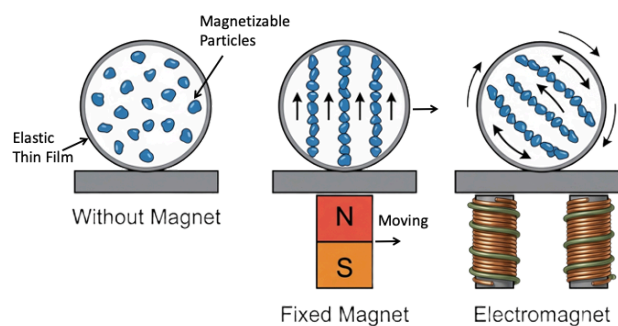


Figure 4. Schematic of particle alignment and macroscopic performance evolution

The rolling actuation is achieved by sequentially switching adjacent electromagnets. When one coil is turned off and the next coil is activated, the strongest magnetic-field region shifts around the encapsulated MRF body. This field shift causes the magnetic particle chains inside the MRF to realign, producing an off-centre magnetic force and therefore a rolling torque. Compared with direct

sliding propulsion, this mechanism allows the robot to advance while reducing continuous shear contact with the surrounding tissue wall.

4.1. Magnetic field modelling

Under quasi-static conditions, the resulting magnetic field is modelled using linear super- position:

$$\mathbf{B}_{\text{total}}(P) = \sum_{i,j} k_{ij}(P) I_{ij} \quad (3)$$

For conceptual analysis, the dipole approximation for Far-Field is:

$$B_z(z) = \frac{\mu_0 \mu_r N I}{2L} \left(\frac{L-2z}{\sqrt{4R^2+(L-2z)^2}} - \frac{-(L+2z)}{\sqrt{4R^2+(L+2z)^2}} \right) \quad (4)$$

Near-Field Solenoid Correction:

$$F_{mag} \approx \chi V \nabla \left(\frac{1}{2} \mu_0 B^2 \right) \quad \text{or} \quad F_{mag} = \nabla (\mathbf{m} \cdot \mathbf{B}) \quad (5)$$

4.2. Force and torque considerations

Magnetic force on MRF:

$$\boldsymbol{\tau}_{mag} = \mathbf{r} \times \mathbf{F}_{mag} \implies \tau_{mag} \approx r_{\perp} F_{mag} \quad (6)$$

Torque generated by the offset vector $\mathbf{r}$:

$$\boldsymbol{\tau}_{mag} = \mathbf{r} \times \mathbf{F}_{mag} \implies \tau_{mag} \approx r_{\perp} F_{mag} \quad (7)$$

Rolling criterion (overcoming resistance):

$$\tau_{mag} > \tau_{res} \implies r_{\perp} F_{mag} > \mu_s N R \quad (8)$$

Coupling and membrane effects:

$$I\ddot{\theta} = \eta \tau_{mag} - \tau_{res} - k_{\theta} \theta - c_{\theta} \dot{\theta} \quad (9)$$

Step displacement:

$$\Delta s \approx \alpha \Delta x \quad (10)$$

5. Phase 2: COMSOL simulation

To theoretically reveal the physical mechanism, a 2D multiphysics coupling simulation model was constructed coupling Magnetic Fields (mf), Laminar Flow (spf), and Phase Field (pf) [16]. The magnetic body force density is calculated as:

$$\mathbf{F} = (\mathbf{M} \cdot \nabla) \mathbf{B} \quad (11)$$

5.1. Geometric model and material settings

The simulation geometry domain is a rectangular region of approximately 40 mm × 20 mm. Three materials were defined: Air as the continuous phase fluid, Engine oil representing the carrier liquid matrix of the MRF droplet, and NGO 50PN350 silicon steel used for the coil core regions to provide high magnetic permeability. The solution process was divided into two steps: phase initialization to establish a stable interface, followed by a transient solution to simulate the dynamic motion under time-varying magnetic fields.

5.2. Simulation results

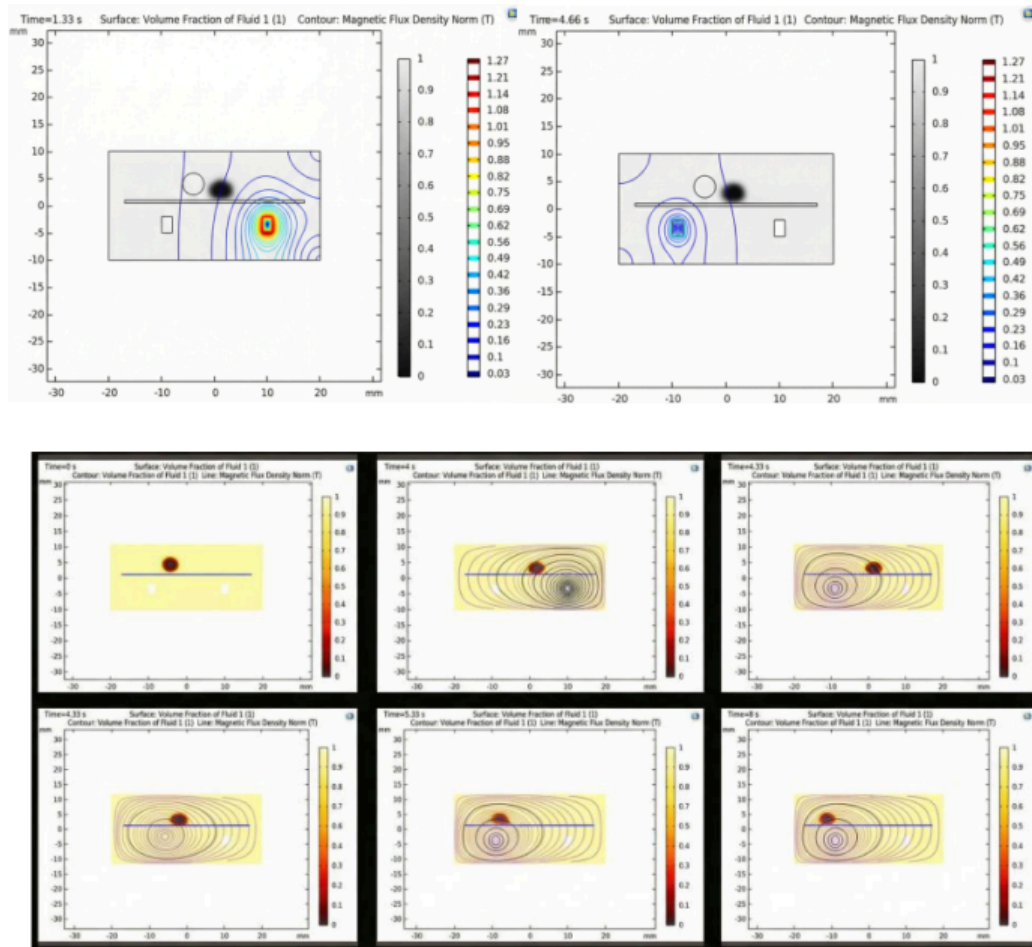


Figure 5. COMSOL simulation results showing spatiotemporal evolution

The simulation results strongly demonstrate that precise control of the motion direction and speed can be achieved by regulating the excitation mode of the electromagnetic coils. As shown in Figure 5, the spatiotemporal evolution of the MRF droplet under sequential electromagnetic excitation confirms the predicted directional displacement.

6. Phase 3: experiment

6.1. Feasibility verification of MRF rolling motion

As shown in Figure 6, the feasibility of the MRF rolling motion was evaluated through a straight-line rolling task. A standard task required the MRF ball to roll 20 cm in a straight line. Out of 50 trials, 46 were successful, corresponding to a 92% success rate. All failures were caused by the MRF ball being obstructed by a protrusion at the sealing point during rolling.

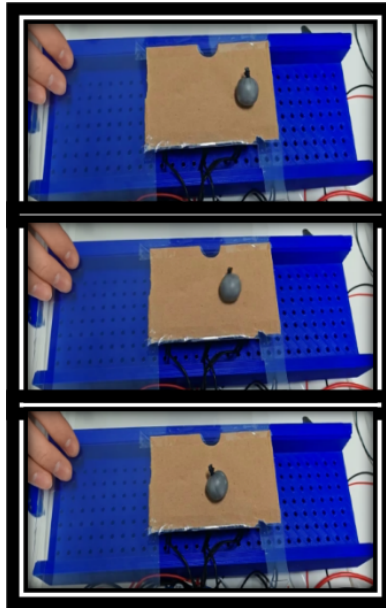


Figure 6. Feasibility verification of MRF rolling motion

6.2. Precise positioning in gastrointestinal scenarios

The test platform consisted of a curved transparent tube representing the gastrointestinal path, an inclined support structure, and a programmable electromagnetic array placed near the target region. The MRF ball was released from the inlet and magnetically stopped near the preset target point.

6.3. Experimental setup and control system

As shown in Figure 7, the experimental platform integrates a 3D-printed ED-shaped simulated digestive tract, a programmable 10-unit electromagnetic array, and an Arduino-based control system. The simulated digestive tract was fabricated via 3D printing using PLA material, with an inner diameter of 20 mm and an S-shaped structure. The bottom integrated a programmable electromagnetic array (12 units) controlled by an Arduino Uno R3. A Buck module stepped down the 12 V DC input to 5 V to power the logic systems, while electromagnets were independently isolated via relay modules.

The MRF balls were formulated by mixing carbonyl iron powder (10–20 μm), medical-grade silicone oil, and targeted drugs in a 7:2:1 volume ratio, encapsulated within a 0.1 mm thick PVC soft-film to form a flexible spherical body. The Arduino program utilized a continuous control loop including input-state monitoring, magnetic-field activation judgment, and relay status control to

independently trigger specific electromagnets for 3 seconds at a 2 A current to achieve targeted anchoring.

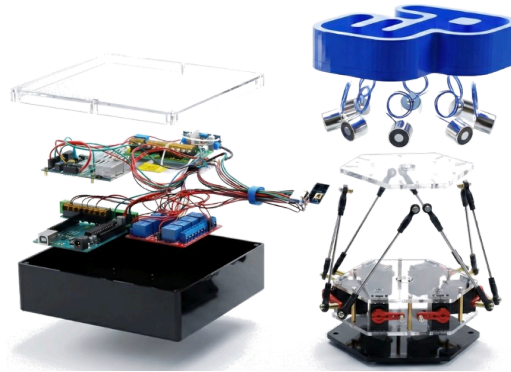


Figure 7. Experimental setup for gastrointestinal positioning, including the simulated digestive tract, electromagnetic array, and control electronics (equipment for Experiment 2)

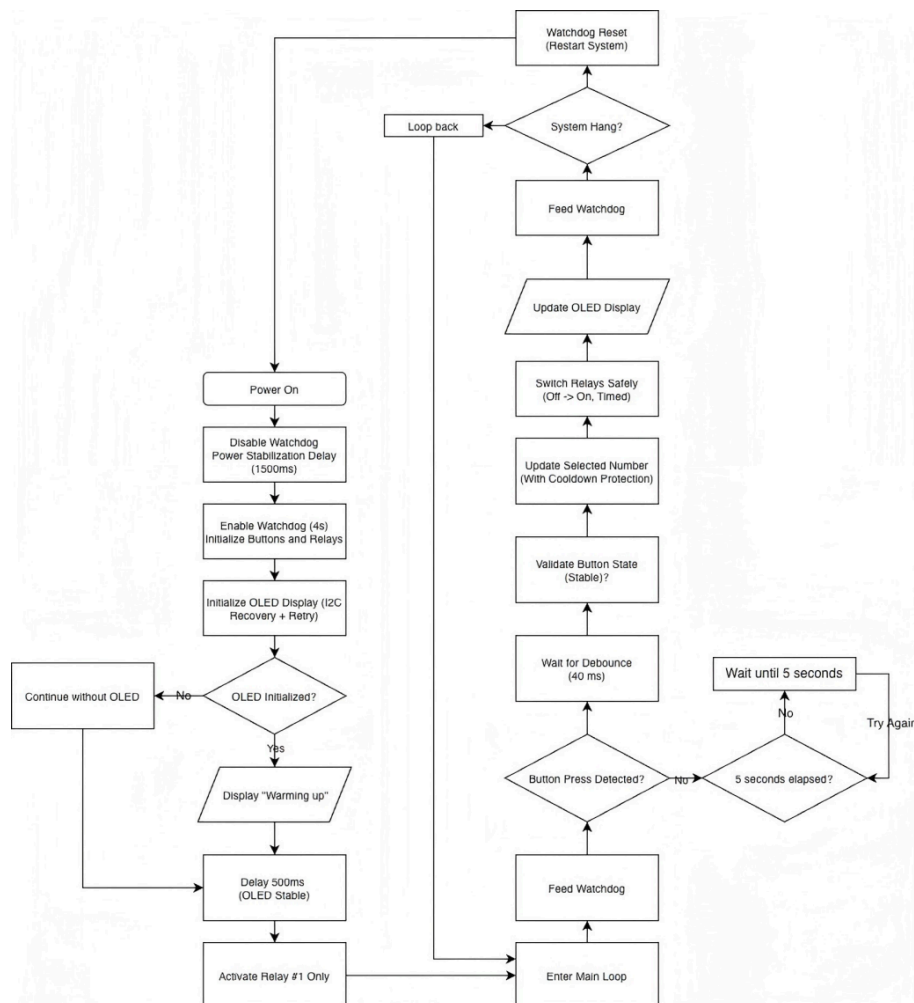


Figure 8. Control program signal flow and system state monitoring module logic (flow diagram)

The Arduino program is written in C++. Its main loop includes the initialization, inputstate monitoring, magnetic-field activation judgment, and relay status control modules. The flowchart is

shown in Figure 8. The signal flow, after power-on, proceeds through OLED initialization, relay status verification, electromagnetic array driving, and finally feeds back to the main controller to determine whether the positioning conditions are met. When the MRF ball enters a preset magnetic zone, the corresponding electromagnetic unit is triggered to output a constant current (2 A), which is maintained for 3 seconds before being turned off, thereby completing one positioning action.

As shown in Figure 9, the MRF ball demonstrated precise positioning capability in a curved gastrointestinal tract. To verify 3D spatial targeting, the MRF ball was deployed in the S-shaped simulated digestive tract at a 40° tilt. Results showed an average targeting error of 0.51 mm (SD = 0.07 mm), demonstrating sub-millimeter precision and repeatable positioning.

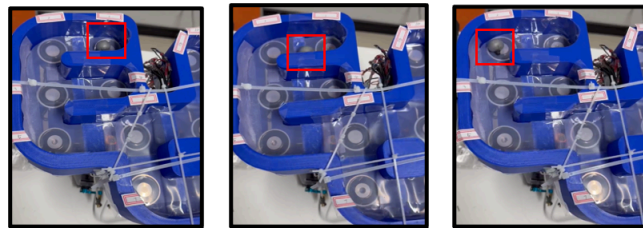


Figure 9. Precise positioning of MRF in gastrointestinal scenarios

6.4. Flow velocity in simulated vascular conditions

A closed-loop tubing system utilizing medical silicone tubing (16 mm inner diameter) and simulated blood (saline-glycerol mixture) was used to reproduce dynamic vascular flow. The MRF microspheres for this scenario were specially formulated with a 6:3:1 mass ratio of carbonyl iron powder (5–10 μm), silicone oil, and a model drug. The electromagnet was activated when the MRF microsphere entered the target window, and successful retention was defined as remaining in the target area for more than 5 seconds [17].

As shown in Figure 10, the magnetic retention performance was evaluated across a range of flow velocities. In the closed-loop hemodynamic simulator (up to 25 L/min), the magnetic field successfully retained the microspheres with a 100% success rate between 6.25 and 12 L/min, and maintained a 70% retention rate at the maximum tested flow of 25 L/min.

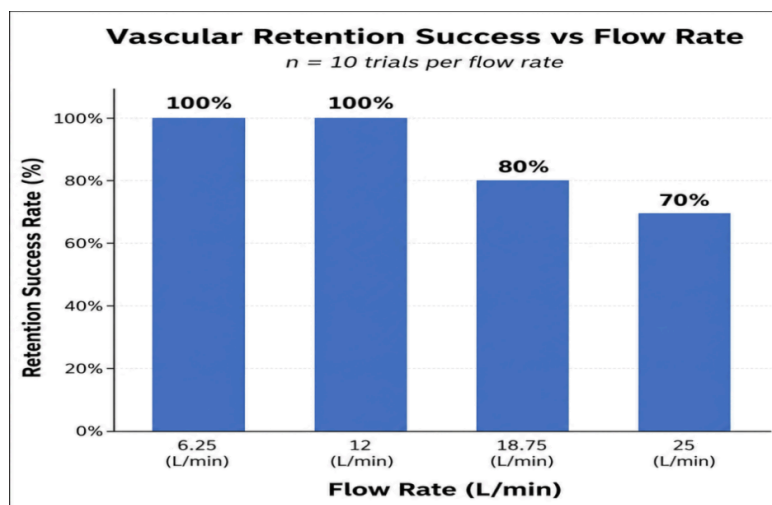


Figure 10. Vascular retention success vs flow rate

6.5. Foreign body removal capacity

As shown in Figure 11, the load transport capacity of the encapsulated MRF was quantitatively evaluated across a range of target weights. The MRF (with a high carbonyl iron concentration of 60 vol%) was magnetically shaped into a gripping structure and used to encapsulate and transport objects over a fixed distance. To quantitatively assess the load capacity, standardized containers with varying water volumes were used to create precise testing loads ranging from 0.5 N to 5.0 N, maintaining uniform contact surfaces across all trials.

The encapsulated MRF maintained a 100% horizontal transport success rate over 5 cm for loads up to 4.5 N. This significantly exceeds the mass of typical intravascular targets (such as thrombi, approx. 0.05–1.0 N).

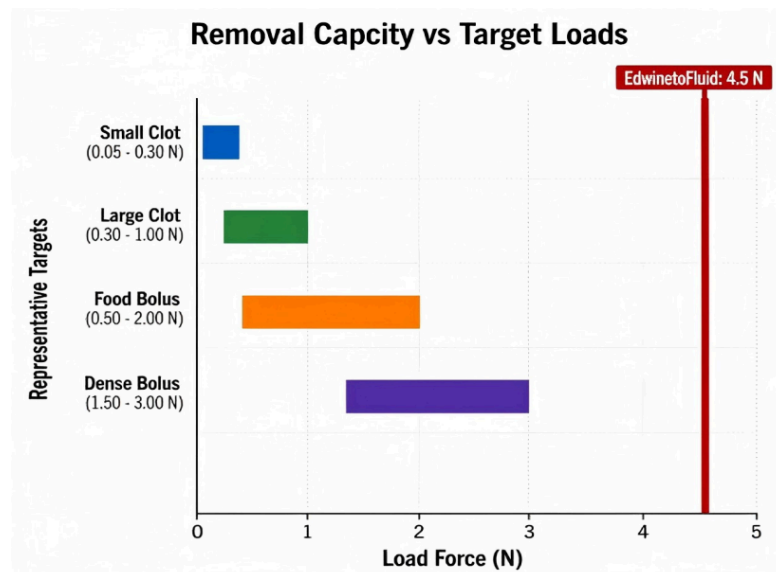


Figure 11. Removal capacity vs target loads

6.6. Comparative experiment on tissue damage: rolling vs. sliding

To simulate the tissue wall interaction, a test bed covered with a waterproof cloth over a rigid substrate was utilized. As shown in Figure 12(a), under the same normal force (1.47 N), free rolling produced a friction force of 0.022 N (rolling friction coefficient $\mu_r = 0.015$) compared to 0.559 N for sliding (sliding friction coefficient $\mu_k = 0.38$) [18-20]. As shown in Figure 12(b), over a 2-second integration period, rolling reduced the cumulative friction impulse by ~96% ($P < 0.001$), confirming its substantial safety advantage.

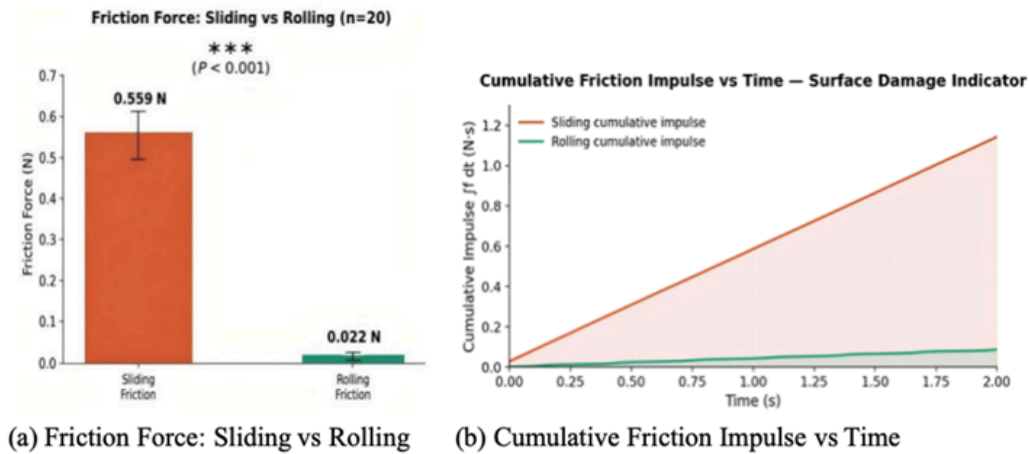


Figure 12. Biomechanical confirmation of rolling safety advantage

7. Conclusion

This study systematically verified the feasibility of a rolling-actuated soft robot concept based on magnetorheological fluid (MRF) driven by externally controlled magnetic field gradients. Through theoretical modelling, COMSOL multiphysics simulation, and proof-of-concept physical experiments, the proposed system demonstrated that encapsulated MRF can be remotely actuated, positioned, and mechanically reconfigured in confined environments. The theoretical analysis established the relationship between magnetic field gradients, magnetic force, and rolling torque, while the simulation results confirmed that sequential electromagnetic excitation can guide directional MRF displacement.

The experimental results further supported the feasibility and safety potential of this approach. The prototype achieved a 92% rolling-task success rate, sub-millimeter gastrointestinal positioning accuracy, stable magnetic retention under simulated vascular flow, and a load capacity of up to 4.5 N. Most importantly, the rolling-sliding comparison showed that rolling motion reduced cumulative friction impulse by approximately 96% under the tested conditions. This result directly supports the central design claim that converting MRF locomotion from a sliding-dominated mode to a rolling-dominated mode can substantially reduce shear interaction with tubular tissue surfaces.

Overall, this work provides a promising proof-of-concept pathway for developing ultra-flexible, tissue-sparing, magnetically controlled soft robotic devices for in-vivo minimally invasive intervention. Although the current system remains at an early experimental stage, the combination of tunable MRF mechanics, wireless magnetic actuation, and rolling-based locomotion offers a distinctive safety advantage for future biomedical robotic systems.

8. Application and next steps

The rolling-driven MRF soft robot proposed in this study has direct application potential in minimally invasive medicine, particularly for cardiovascular and gastrointestinal interventions. In the digestive tract, the robot could be used for foreign body removal, targeted drug delivery, or endoscopic surgical assistance. Its flexible encapsulation and magnetically controlled grasping capability may allow hazardous objects, such as button batteries or small foreign bodies, to be removed with less mechanical trauma than conventional rigid instruments. In vascular scenarios, the same principle could support contact-based thrombus clearance by enabling local anchoring,

controlled deformation, and targeted mechanical interaction with clot-like obstructions. These applications address current clinical limitations such as high invasiveness, limited precision, high operator skill requirements, and the inability of systemic drugs to act immediately at the target site.

Future work should focus on three main directions. First, the mechanical design and fabrication process should be improved, especially the encapsulation structure, because sealing protrusions were identified as the major cause of rolling failure. Optimizing the shell geometry, sealing method, and material uniformity could further improve reliability and repeatability. Second, a more complete magneto-force-motion coupled model should be developed to predict MRF deformation, rolling displacement, and interaction forces under different tube geometries and flow conditions. This would support more accurate electromagnetic control and reduce dependence on trial-and-error tuning.

Third, the system should be advanced toward biomedical translation. This requires developing fully biocompatible MRF formulations and encapsulation materials, integrating miniature sensing modules such as cameras or pressure sensors for closed-loop feedback, and testing the robot in more realistic physiological environments, including dynamic blood flow, gastric fluid, curved vessels, and deformable tissue-like surfaces. Long-term safety, material stability, and efficacy should then be evaluated through preclinical animal studies. The ultimate goal is to move this technology from a laboratory proof-of-concept platform toward a clinically relevant ultra-minimally invasive diagnostic and therapeutic platform.

References

- [1] Alkarithi, Ghadir, et al. "Thrombus structural composition in cardiovascular disease." *Arteriosclerosis, thrombosis, and vascular biology* 41.9 (2021): 2370-2383.
- [2] Mackie, Alan. "The digestive tract: A complex system." *Interdisciplinary approaches to food digestion*. Cham: Springer International Publishing, 2019. 11-27.
- [3] Alvarez, Walter Clement. *The mechanics of the digestive tract: an introduction to gastroenterology*. Hoeber, 1928.
- [4] Lee, Chiwon, et al. "Soft robot review." *International Journal of Control, Automation and Systems* 15.1 (2017): 3-15.
- [5] Balak, Roman, and Yi Chen Mazumdar. "Bistable valves for MR fluid-based soft robotic actuation systems." *IEEE Robotics and Automation Letters* 6.4 (2021): 8285- 8292.
- [6] Calisti, Marcello, Giacomo Picardi, and Cecilia Laschi. "Fundamentals of soft robot locomotion." *Journal of The Royal Society Interface* 14.130 (2017): 20170101.
- [7] Bira, Nicholas, Pallavi Dhagat, and Joseph R. Davidson. "A review of magnetic elastomers and their role in soft robotics." *Frontiers in Robotics and AI* 7 (2020): 588391.
- [8] De Vicente, Juan, Daniel J. Klingenberg, and Roque Hidalgo-Alvarez. "Magnetorheological fluids: a review." *Soft matter* 7.8 (2011): 3701-3710.
- [9] Ashtiani, M., S. H. Hashemabadi, and A. Ghaffari. "A review on the magnetorheological fluid preparation and stabilization." *Journal of magnetism and Magnetic Materials* 374 (2015): 716-730.
- [10] Ashour, Osama, Craig A. Rogers, and William Kordonsky. "Magnetorheological fluids: materials, characterization, and devices." *Journal of intelligent material systems and structures* 7.2 (1996): 123-130.
- [11] McDonald, Kevin, et al. "Magnetorheological fluid-based flow control for soft robots." *Advanced Intelligent Systems* 2.11 (2020): 2000139.
- [12] Hua, Dezheng, et al. "A magnetorheological fluid-filled soft crawling robot with magnetic actuation." *IEEE/ASME Transactions on Mechatronics* 25.6 (2020): 2700- 2710.
- [13] Li, Lin, et al. "Magnetorheological fluid for adaptive soft robotics." *IEEE Robotics and Automation Letters* (2024).
- [14] Grant, Ian S., and William Robert Phillips. *Electromagnetism*. John Wiley & Sons, 2013.
- [15] Belot, Gordon. "Understanding electromagnetism." *The British Journal for the Philosophy of Science* 49.4 (1998): 531-555.
- [16] Ghaffari, Ali, Seyed Hassan Hashemabadi, and Mahshid Ashtiani. "A review on the simulation and modeling of magnetorheological fluids." *Journal of intelligent material systems and structures* 26.8 (2015): 881-904.

- [17] Zitha, P. L. J., and F. Wessel. "Fluid flow control using magnetorheological fluids." SPE Improved Oil Recovery Conference. SPE, 2002.
- [18] Persson, Bo NJ. Sliding friction: physical principles and applications. Springer Science & Business Media, 2013.
- [19] Reynolds, Osborne. "VI. On rolling-friction." Philosophical Transactions of the Royal Society of London 166 (1876): 155-174.
- [20] Flom, D. G., and A. M. Bueche. "Theory of rolling friction for spheres." Journal of Applied Physics 30.11 (1959): 1725-1730.