Magnetic Microrobots as a Platform for Cell Clean Up

Fatma Ceren Kirmizitas[1,2], David Rivas[1], Sudipta Mallick[1], Scott DePope[1], Sambeeta Das[1]

***Abstract*— Mobile magnetic microrobots have been extensively used in a wide range of biomedical applications due to their numerous advantages. Magnetic microrobots in particular have been developed and shown great potential over the past two decades for the manipulation and migration of both single cells and cell aggregates. The efficient clearance of cell aggregates is crucial to prevent uncontrolled cell proliferation, tissue damage, and invasive surgeries, especially for those related to the vascular system. In this work, we showed cellular manipulation and mobility to achieve cellular clean up on Human Liver Cancer (HepG2) cells by using two types of untethered magnetic microrobots that are different in type and size. We performed the cellular clean up in the microchannel, which can demonstrate the closed working environment, and also on a glass slide to present an air-liquid interface. We showed that the microrobots could be able to move a cluster of cells in both conditions which could make them useful for sorting and separation applications. Furthermore, cell viability was assessed by using a trypan blue staining assay on HepG2 cells right after and 24 hours after microrobot actuation.**

***Index Terms* — Magnetic Microrobots, Single-Cell Manipulation, Cell Clean up**

I. INTRODUCTION

Microrobots have shown immense potential in biomedical applications such as drug delivery, cell manipulation, imaging, cell sorting, and labeling [1]–[6]. Single-cell manipulation is one of the major applications that has captured the attention of cell biologists. Cell manipulation has been presented via different methods from different research groups [7]–[10]. In the early 21st century, cell manipulation was achieved via pipette, and more recently via optical tweezers, electrical forces, or specially designed microfluidic channel systems [11]. Alternatively, mobile magnetic microrobots are great candidates for cell manipulation since they are minimally invasive, versatile, small in size, remotely controlled, and accepted as harmless for biomedical applications [11]–[13]. Cellular manipulation with magnetic microrobots is preferred over optical manipulation when considering cytotoxicity, adequate driving force, and convenient working tools such as electromagnetic coils. Magnetic microrobots have been designed and employed for single-cell manipulation tasks over the past years [14]–[18]. As a promising technique for manipulating single-cell, magnetic microrobots provide precise and remotely controlled interactions with individual cells and also avoid contamination risk since they are untethered and the working system is closed [19].

Cell removal and cleanup is an essential task in many surgical procedures for example cell debris and dead cell clearance after thrombosis or tumor surgery. One such application is in removal of blood clots. Blood clots lead to blocksed the blood vessels and can cause severe cardiovascular issues and even death [20], [21]. The existing thrombolytic drugs can be effective but their delivery is inefficient because of the difficulty of penetration inside the thrombus. Recently, magnetic particles, nanoparticles, and nanodroplets have been studied for removing blood clots [21]–[24]. Magnetic microrobots in particular have the potential to effectively dissolve and remove the clots from the blood vessels [25]–[28]. Following the removal of the clot, it is also necessary to clean the dead cells and cellular debris from the affected area. In theory, a biological process in the body called phagocytosis generally removes these cells, however, in practice, faster and more efficient removal of the debris requires extra agents [29]. Another area where cell removal is critical tends to be tumor removal surgery. A tumor can be removed by surgery, however, it is known that the first surgery cannot remove all the cancer cells from the tumor site. An additional surgery called debulking surgery is needed to remove as many cancer cells as possible from the tumor site which means an additional invasive and harmful operation for the patient [30].

Thus traditional surgical techniques tend to ineffective for total cell removal since the hard-to-reach areas tend to closer to the size of the cells. Microrobots offer a distinct advantage in this case since the microrobot size and characteristics can be chosen according to the target site. Every organ has a different penetration depth, size, and navigation route [31]. The sizes of microrobots can therefore changeed to take into account the practicality and cell manipulation efficiency [32]. In particular, smaller microrobots are beneficial for being minimally invasive, but they also suffer from the lack of precise control [11].

In this study, we aim to overcome this problem by using small magnetically driven microrobots for cell manipulation, removal, and cleanup. To demonstrate cell manipulation and migration we use two differently sized magnetic microrobots inside a microchannel and on a glass slide as an air-liquid interface. These demonstrate the precise control and effectiveness of our magnetic microrobots. Firstly, we placed the microrobots on a glass slide with a dense population of mammalian cells. Microrobots could move and manipulate the cells through a pushing mechanism. Secondly, we used two types of magnetic microrobots (hollow silica based

[1]Department of Mechanical Engineering, and [2]Department of Animal and Food Sciences, University of Delaware, Newark, DE 19716. (emails:ceren@udel.edu; drivas@udel.edu; sudipta@udel.edu; sdepope@udel.edu;samdas@udel.edu.)

and solid ferromagnetic) inside a microchannel to navigate around the mammalian cells and remove the cell aggregates from the target area, respectively. Cell viability was also assessed by trypan blue assay immediately after and 24 hours after actuation with the ferromagnetic microrobots.

II. Materials and Methods

A. Experimental Procedures

To perform the cellular manipulation experiments, cells were mixed with the two types of microrobots: hollow silica based and solid ferromagnetic. Next, the samples were introduced to commercially available microchannels (Darwin Microfluidics, France) with 200 μm width and depth and the glass slide, separately. Experiments were conducted with a Zeiss Axiovert 200 inverted microscope and videos were acquired using an Amscope MU903-65 camera.

B. Fabrication of Microrobots

Hollow 45-85 μm magnetic microrobots were made by depositing a 100 nm layer of nickel by e-beam deposition on the spherical microrobots. The hollow microrobots are made of silica (Cospheric) and have a thin TiO_2 layer on their surface. The nickel layer was deposited at a glancing angle of 70 degrees from the surface normal which generally reduces the amount of nickel coating due to a shadowing effect. We found that the microrobots with a small surface coverage of nickel result in a magnetic moment tangent to the surface of the microrobot [17]. Ferromagnetic particles of 2.0 μm diameter were purchased from Spherotech Inc, USA, and used without any further modification.

C. Electromagnetic System

Magnetic fields were applied using a custom-built three-axis electromagnetic system consisting of pairs of coils along the x, y, and z axes [33] (Fig. 1). The amount and direction of the current that was sent through each coil were controlled via an X-box controller which communicated to custom Matlab and Python software, as described in more detail in Ref. [33]. To roll the microrobots, rotating magnetic fields were applied according to the following equations,

$$B_x = -A[\cos(\gamma)\cos(\alpha)\cos(\omega t) + \sin(\alpha)\sin(\omega t)] \quad (1)$$

$$B_y = A[-\cos(\gamma)\sin(\alpha)\cos(\omega t) + (\cos(\alpha)\sin(\omega t)] \quad (2)$$

$$B_z = A\sin(\gamma)\cos(\omega t) \quad (3)$$

Where γ is the azimuthal angle from the z axis, α is the polar angle from the x axis, A is the magnetic field magnitude, and ω is the frequency that controls the speed of the rolling microrobot. An azimuthal angle of 90° was used in all of the experiments presented here.

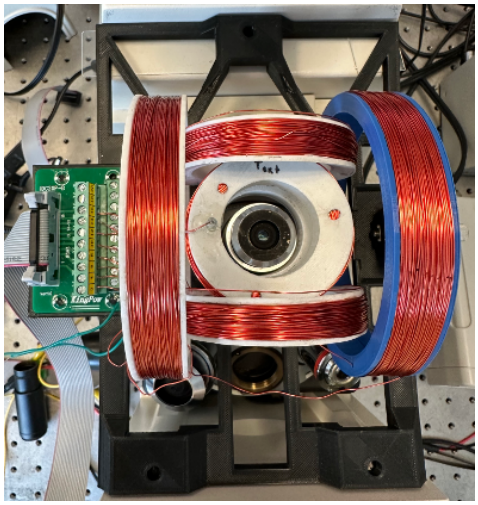

Fig. 1: Experimental setup.

D. Cell Maintenance

Hepatocellular Carcinoma cells (HepG2) were used as a representative cell line for demonstrating cellular manipulation and mobility. Cells were gifted by Richard West (Associate Scientist at Flow Cytometry Core Facility). Cells were cultured in Dulbecco's Modified Essential Medium (DMEM, Gibco, BenchStable, USA) media supplemented with 10% Fetal Bovine Serum (FBS) and 1% penicillin-streptomycin in a humidified cell culture incubator at 37 °C with 5% CO_2. Cells were used after their third passage. Prior to the experiments, cells were washed with Dulbecco's phosphate-buffered saline (DPBS) (Gibco, BenchStable, USA) and trypsinized to detach cells from the culture flask.

To determine the post-treatment cell viability, trypan blue staining assay was performed to identify the number of live/dead cells. Cells were cultured overnight under standard culture conditions with the microrobots 1×10^5 cells/ml per well in a 6-well plate (Costar, Corning, USA). After, the media was centrifuged and resuspended in Phosphate Buffer Saline (PBS) (Gibco, BenchStable, USA). A 10 µl of cell suspension was mixed 1:1 (v/v) with 0.4% trypan blue, and cells were counted in a cell counter (Nexcelom Cellometer Vision Trio Cell Profiler, USA). Cell morphology after staining was also observed under an optical microscope (ZOE Fluorescent Cell Imager, USA) after microrobot treatment. Furthermore, cell viability after ferromagnetic microrobot actuation was determined on HepG2 cells. Subsequently, after microrobot actuation under a constant magnetic field, cells were cultured for 24 hours at the standard cell culture conditions. The cells were observed under the optical microscope directly after and 24 hours after the actuation.

III. Results and Discussion

A. Cell Viability

Biocompatibility is one of the most crucial factors for biomedical applications of microrobots. The microrobots

should be non-toxic, non-immunogenic, and cytocompatible to be used with the cells. The hollow silica based microrobots do not have any toxic effect on viable cells [17] and thus are a viable candidate for cell manipulation studies. For the ferromagnetic particles, we performed trypan blue cell viability assay on them. Cells were incubated with microrobots for 24 hours and, as shown in Fig. 2, cell viability was 90%, and cell morphology was intact when compared with the non-treated cell group. Fig. 3 depicts the cells immediately after and 24 hours after the actuation. It can be seen that cell morphology and cell proliferation was intact. The results revealed that the ferromagnetic microrobots are well-tolerated by the cells, non-toxic, and suitable for further studies.

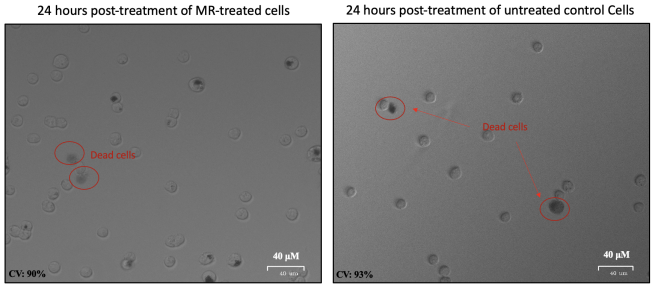

Fig. 2: Images of cell viability of ferromagnetic microrobots on HepG2 cells after 24 hours of incubation. Cell viability was 90% for microrobot-treated cells. CV represents the cell viability.

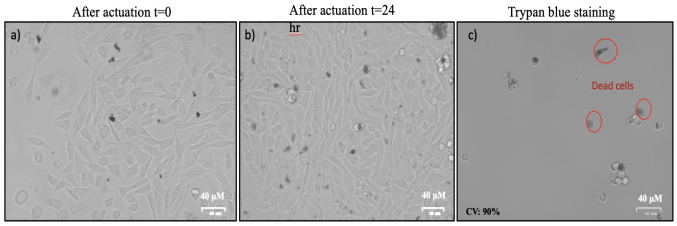

Fig. 3: Images of HepG2 cells immediately after (a) and 24 hours after (b) ferromagnetic microrobot actuation. Cell viability was 90% after actuation (c). Dead cells are stained and shown in red circles. CV represents cell viability.

B. Cell Manipulation

To demonstrate single-cell manipulation on air-liquid interface via hollow microrobots, we used HepG2 cells on the glass slide. Fig. 4 shows the hollow silica based microrobots manipulating cells. Hollow microrobots tend to stick to cells which is important in cell manipulation studies, since adhesion between the cells and microrobots is considered to be one of the key factors for cell manipulation [32]. Strong adhesion enables the microrobots to move and carry the cells safely and precisely to the target site.

The supporting video demonstrates that hollow microrobots can be used to move cell aggregates on

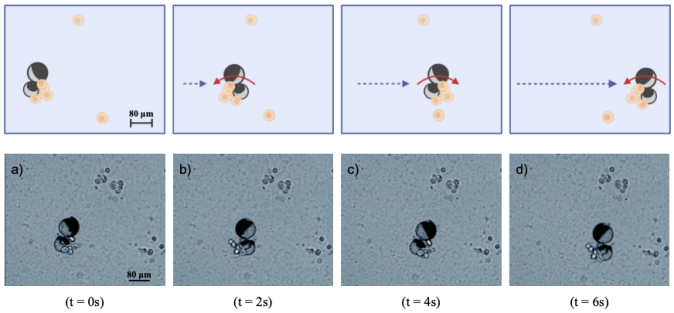

Fig. 4: Images of hollow microrobots carrying a group of HepG2 cells.

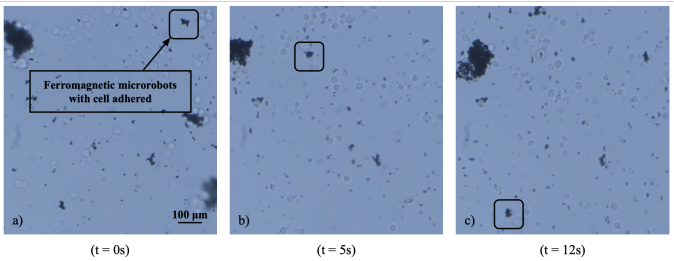

Fig. 5: Images of single-cell manipulation (a-c) via a ferromagnetic microrobot cluster

the glass slide. In Fig 4, it is shown that the hollow microrobots are able to manipulate a group of cells by pushing and releasing them. Once adhered to the cells, they carry and release them by using a spinning motion. As in Fig. 4, the adhesion of microrobots and cells was strong which helps the controllability of the cell manipulation. We hypothesize that these microrobots can adhere to the cells due to Van der Walls or electrostatic interactions between these cells and microrobots [17].

In addition, we used ferromagnetic microrobots to demonstrate cell manipulation on the glass slide as well. Fig. 5, Fig. 6, and the supporting video shows that once the ferromagnetic microrobots were driven to cells, they can attach to the cells, and are able to move the cells by changing the magnetic field. Due to the strong response to the magnetic field of hollow silica and ferromagnetic microrobots, both single HepG2 and cell aggregates can be transported. For mobile magnetic microrobots, pushing-based interaction is one of the most implemented approaches in cell manipulation. For example, there are studies that use mobile magnetic microrobots to move cell aggregates by instant binding [34], [35]. The results strongly indicate that the our magnetic microrobots have the potential to be used in cell migration and capturing cell aggregates in the liquid cell culture media environment without additional complex surface modifications.

C. Cell Clean up

In this study, we also used hollow silica and ferromagnetic particles to remove cell aggregates placed inside a microchannel. Microchannels can serve as a model for

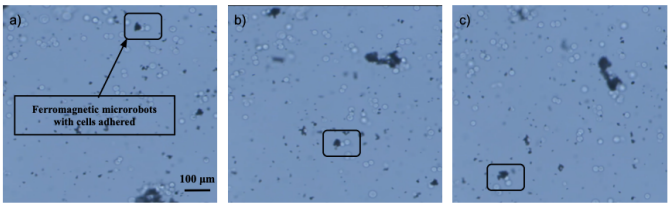

Fig. 6: Images of ferromagnetic microrobots carrying HepG2 cells.

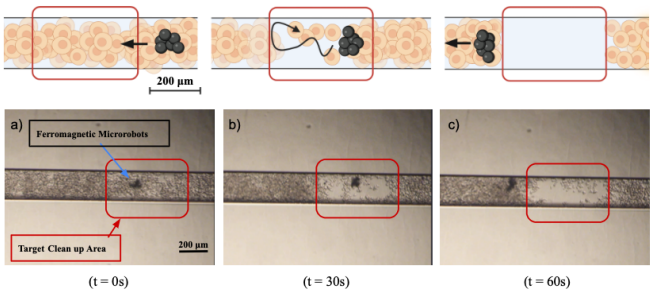

Fig. 7: Step-by-step images of ferromagnetic microrobots cell clean up process. Firstly, microrobots approached the target site (a), tumbled to remove the cells from the target site (b), and left the area after cell clean up (c).

blood vessels [36]–[38]. Clot removal studies have been previously done with the magnetic helical microdrillers [39] and nanodroplets [40] by creating clot models inside the microfluidic channels, as they can go around or toward the cells to move and spread the cell aggregates. In addition, they can be candidates to work in the center of the thrombus, which is dense due to the high concentration of fibrin, and is hard to reach in most cases. As shown in Fig 7 and Fig 8, the microrobots were placed at the target site and rotated together with the cells. After the rotation motion of microrobots, a significant amount of cell aggregates fell apart and left the target site after given time points. As seen in Fig 7, the ferromagnetic microrobots form clusters and move along the surface via a tumbling motion following the magnetic field application. These particles tend to form clusters or chains because of dipole-dipole interactions between the particles themselves and these clusters move along their long axis [41].

Removing cell debris from the target site is a serious issue for various in vitro and clinical applications. Post-surgery treatments may depend on the clearance of the target site from the cellular debris and dead cells. Both in Fig. 7 and Fig. 8, we demonstrated the efficient cell clean-up via the microrobots can be promising for fast, efficient, and non-invasive cellular debris clean-up. Even though the size is significantly different between these two types of microrobots, both of them were able to spread the cell aggregates. We also want to highlight that, in this study, we did not apply any drugs to move the cell aggregates. The microrobots were able to clean the cells adhering to the channel walls and inner part using only mechanical motion.

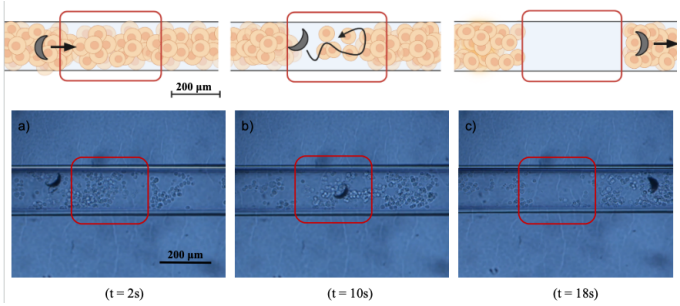

Fig. 8: Step-by-step images of a hollow microrobot cell clean up process. Firstly, microrobots approached the target site (a), tumbled to remove the cells from the target site (b), and left the area after cell clean up (c).

IV. CONCLUSIONS

The magnetic microrobots' versatility, cytocompatibility, and simple handling make them promising agents in biological and chemical applications. We have achieved cell manipulation and migration via ferromagnetic and hollow silica based microrobots both on the glass slide and inside a microchannel. Significantly, we observed that both microrobots could disperse HepG2 cell aggregates via only mechanical forces without using any drugs or chemicals. In addition to cell migration, experimental results showed that these magnetic microrobots can be precisely controlled and navigated in cell-dense environments which is promising for both *in vitro* and *in vivo* applications. The microfluidic channels were used as a representative of blood vessels to show clot removal in channels by the microrobots.

V. ACKNOWLEDGMENTS

This work was supported by the National Science Foundation under grant GCR 2219101 and the National Health Institute under grant 1R35GM147451. This project was also supported with a grant from the National Institute of General Medical Sciences – NIGMS (5P20GM109021-07) from the National Institutes of Health and the State of Delaware.

REFERENCES

[1] M. Sitti, H. Ceylan, W. Hu, J. Giltinan, M. Turan, S. Yim, and E. Diller, "Biomedical applications of untethered mobile milli/microrobots," *Proceedings of the IEEE*, vol. 103, no. 2, pp. 205–224, 2015.

[2] X.-Z. Chen, M. Hoop, F. Mushtaq, E. Siringil, C. Hu, B. J. Nelson, and S. Pané, "Recent developments in magnetically driven micro-and nanorobots," *Applied Materials Today*, vol. 9, pp. 37–48, 2017.

[3] Z. H. Shah, B. Wu, and S. Das, "Multistimuli-responsive microrobots: A comprehensive review," *Frontiers in Robotics and AI*, vol. 9, p. 1027415, 2022.

[4] Z. H. Shah, M. Sockolich, D. Rivas, and S. Das, "Fabrication and open-loop control of three-lobed nonspherical janus microrobots," *MRS Advances*, pp. 1–5, 2023.

[5] D. P. Rivas, M. Sokolich, and s. Das, "Spatial patterning of micromotor aggregation and flux," *ChemNanoMat*, p. e202300225.

[6] L. E. Beaver, B. Wu, S. Das, and A. A. Malikopoulos, "A first-order approach to model simultaneous control of multiple microrobots," in *2022 International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS)*. IEEE, 2022, pp. 1–7.

[7] D. Ahmed, T. Baasch, B. Jang, S. Pane, J. Dual, and B. J. Nelson, "Artificial swimmers propelled by acoustically activated flagella," *Nano letters*, vol. 16, no. 8, pp. 4968–4974, 2016.

[8] J.-F. Louf, N. Bertin, B. Dollet, O. Stephan, and P. Marmottant, "Hovering microswimmers exhibit ultrafast motion to navigate under acoustic forces," *Advanced Materials Interfaces*, vol. 5, no. 16, p. 1800425, 2018.

[9] S. Das, E. E. Hunter, N. A. DeLateur, E. B. Steager, R. Weiss, and V. Kumar, "Controlled delivery of signaling molecules using magnetic microrobots," in *2018 international conference on manipulation, automation and robotics at small scales (MARSS)*. IEEE, 2018, pp. 1–5.

[10] ——, "Cellular expression through morphogen delivery by light activated magnetic microrobots," *Journal of Micro-Bio Robotics*, vol. 15, pp. 79–90, 2019.

[11] E. B. Steager, M. Selman Sakar, C. Magee, M. Kennedy, A. Cowley, and V. Kumar, "Automated biomanipulation of single cells using magnetic microrobots," *The International Journal of Robotics Research*, vol. 32, no. 3, pp. 346–359, 2013.

[12] M. Sokolich, D. Rivas, Z. H. Shah, and S. Das, "Automated control of catalytic janus micromotors," *MRS Advances*, pp. 1–5, 2023.

[13] S. Mallick, R. Abouomar, D. Rivas, M. Sokolich, F. C. Kirmizitas, A. Dutta, and S. Das, "Doxorubicin-loaded microrobots for targeted drug delivery and anticancer therapy." *Advanced Healthcare Materials*, pp. e2 300 939–e2 300 939, 2023.

[14] A. Shakoor, W. Gao, L. Zhao, Z. Jiang, and D. Sun, "Advanced tools and methods for single-cell surgery," *Microsystems & Nanoengineering*, vol. 8, no. 1, p. 47, 2022.

[15] T. Pan, Y. Shi, N. Zhao, J. Xiong, Y. Xiao, H. Xin, and B. Li, "Bio-micromotor tweezers for noninvasive bio-cargo delivery and precise therapy," *Advanced Functional Materials*, vol. 32, no. 16, p. 2111038, 2022.

[16] Y. Tsatskis, M. Zhu, F. Wang, *et al.*, "Intracellular manipulation and measurement with multipole magnetic tweezers," *Science robotics*, vol. 4, no. 28, p. eaav6180, 2019.

[17] D. Rivas, S. Mallick, M. Sokolich, and S. Das, "Cellular manipulation using rolling microrobots," in *2022 International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS)*. IEEE, 2022, pp. 1–6.

[18] M. M. Rahman, T. Garudadri, and S. Das, "Role of surface tension in microrobot penetration in membranes," in *2022 International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS)*. IEEE, 2022, pp. 1–6.

[19] L. Feng, X. Wu, Y. Jiang, D. Zhang, and F. Arai, "Manipulating microrobots using balanced magnetic and buoyancy forces," *Micromachines*, vol. 9, no. 2, p. 50, 2018.

[20] N. Mackman, "Triggers, targets and treatments for thrombosis," *Nature*, vol. 451, no. 7181, pp. 914–918, 2008.

[21] Y. Pan, Y. Li, Y. Li, X. Zheng, C. Zou, J. Li, and H. Chen, "Nanodroplet-coated microbubbles used in sonothrombolysis with two-step cavitation strategy," *Advanced Healthcare Materials*, vol. 12, no. 6, p. 2202281, 2023.

[22] X. Zheng, Y. Pan, Y. Zhang, K. Meng, J. Zhou, X. Wang, Y. Cui, J. Li, Y. Li, and H. Chen, "Interventional microbubble enhanced sonothrombolysis on left ventricular assist devices," *Advanced Science*, vol. 9, no. 21, p. 2201291, 2022.

[23] L. Goel, H. Wu, B. Zhang, J. Kim, P. A. Dayton, Z. Xu, and X. Jiang, "Safety evaluation of a forward-viewing intravascular transducer for sonothrombolysis: An in vitro and ex vivo study," *Ultrasound in Medicine & Biology*, vol. 47, no. 11, pp. 3231–3239, 2021.

[24] N. Korin, M. Kanapathipillai, B. D. Matthews, M. Crescente, A. Brill, T. Mammoto, K. Ghosh, S. Jurek, S. A. Bencherif, D. Bhatta, *et al.*, "Shear-activated nanotherapeutics for drug targeting to obstructed blood vessels," *Science*, vol. 337, no. 6095, pp. 738–742, 2012.

[25] I. S. Khalil, A. F. Tabak, K. Sadek, D. Mahdy, N. Hamdi, and M. Sitti, "Rubbing against blood clots using helical robots: Modeling and in vitro experimental validation," *IEEE Robotics and Automation Letters*, vol. 2, no. 2, pp. 927–934, 2017.

[26] I. S. Khalil, A. Adel, D. Mahdy, M. M. Micheal, M. Mansour, N. Hamdi, and S. Misra, "Magnetic localization and control of helical robots for clearing superficial blood clots," *APL bioengineering*, vol. 3, no. 2, p. 026104, 2019.

[27] Q. Yang, A. Enriquez, D. Devathasan, C. A. Thompson, D. Nayee, R. Harris, D. Satoski, B. Obeng-Gyasi, A. Lee, and T. R. Bentley, "Application of magnetically actuated self-clearing catheter for rapid in situ blood clot clearance in hemorrhagic stroke treatment," *Nature Communications*, vol. 13, no. 1, p. 520, 2022.

[28] A. Moghanizadeh, M. Khanzadi, and M. Rajabi, "Eliminating vascular obstruction in myocardial infarction by accelerated ferromagnetic microrobot," 2021.

[29] S.-M. Ting, X. Zhao, G. Sun, L. Obertas, M. Ricote, and J. Aronowski, "Brain cleanup as a potential target for poststroke recovery: the role of rxr (retinoic x receptor) in phagocytes," *Stroke*, vol. 51, no. 3, pp. 958–966, 2020.

[30] Y. J. Song, "Prediction of optimal debulking surgery in ovarian cancer," *Gland surgery*, vol. 10, no. 3, p. 1173, 2021.

[31] R. Nauber, S. R. Goudu, M. Goeckenjan, M. Bornha user, C. Ribeiro, and M. Medina-Sanchez, "Medical microrobots in reproductive medicine from the bench to the clinic," *Nature Communications*, vol. 14, no. 1, p. 728, 2023.

[32] B. Ahmad, M. Gauthier, G. J. Laurent, and A. Bolopion, "Mobile microrobots for in vitro biomedical applications: A survey," *IEEE Transactions on Robotics*, vol. 38, no. 1, pp. 646–663, 2021.

[33] M. Sokolich, D. Rivas, Y. Yang, M. Duey, and S. Das, "Modmag: A modular magnetic micro-robotic manipulation device," *MethodsX*, vol. 10, p. 102171, 2023.

[34] K. Villa, L. Krejcova, F. Novotny, Z. Heger, Z. Sofer, and M. Pumera, "Cooperative multifunctional self-propelled paramagnetic microrobots with chemical handles for cell manipulation and drug delivery," *Advanced Functional Materials*, vol. 28, no. 43, p. 1804343, 2018.

[35] J. Li, H. Wang, Q. Shi, Z. Zheng, J. Cui, T. Sun, P. Ferraro, Q. Huang, and T. Fukuda, "Biped walking of magnetic microrobot in oscillating field for indirect manipulation of non-magnetic objects," *IEEE Transactions on Nanotechnology*, vol. 19, pp. 21–24, 2019.

[36] D. Bento, S. Lopes, I. Maia, R. Lima, and J. M. Miranda, "Bubbles moving in blood flow in a microchannel network: The effect on the local hematocrit," *Micromachines*, vol. 11, no. 4, p. 344, 2020.

[37] R. O. Rodrigues, R. Lopes, D. Pinho, A. I. Pereira, V. Garcia, S. Gassmann, P. C. Sousa, and R. Lima, "In vitro blood flow and cell-free layer in hyperbolic microchannels: Visualizations and measurements," *BioChip Journal*, vol. 10, pp. 9–15, 2016.

[38] H. Fujiwara, T. Ishikawa, R. Lima, N. Matsuki, Y. Imai, H. Kaji, M. Nishizawa, and T. Yamaguchi, "Red blood cell motions in high-hematocrit blood flowing through a stenosed microchannel," *Journal of Biomechanics*, vol. 42, no. 7, pp. 838–843, 2009.

[39] Y. Hou, H. Wang, S. Zhong, Y. Qiu, Q. Shi, T. Sun, Q. Huang, and T. Fukuda, "Design and control of a surface-dimple-optimized helical microdrill for motions in high-viscosity fluids," *IEEE/ASME Transactions on Mechatronics*, 2022.

[40] L. Goel, H. Wu, B. Zhang, J. Kim, P. A. Dayton, Z. Xu, and X. Jiang, "Nanodroplet-mediated catheter-directed sonothrombolysis of retracted blood clots," *Microsystems & nanoengineering*, vol. 7, no. 1, p. 3, 2021.

[41] H. Morimoto, T. Ukai, Y. Nagaoka, N. Grobert, and T. Maekawa, "Tumbling motion of magnetic particles on a magnetic substrate induced by a rotational magnetic field," *Physical Review E*, vol. 78, no. 2, p. 021403, 2008.