Magnetically Actuated Capsule Mechanism for Drug Delivery, Sampling, and Cargo Transport in the Gastrointestinal Tract

Shivam Gupta*, Veerash Palanichamy*, and Onaizah Onaizah

Abstract—Wireless capsule endoscopes are often limited to imaging applications and can lack active control capabilities. Over the last two decades, a growing body of research in medical robotics has introduced active actuation. Embedding magnetic components inside these devices is one of the ways to achieve this; however, most of these tools are still limited to a single function, such as drug delivery, sampling, or imaging. Multifunctional capsules that can perform several different tasks can be used for a range of biomedical applications, leading to easy adoption due to their versatility. In this study, we present a novel magnetically actuated capsule with a spring-magnet mechanism designed for drug delivery, microbiome sampling, and cargo transport. The capsule is remotely actuated using external magnetic fields generated by a permanent magnet. It can be ingested orally, activated at a target location for drug delivery, microbiome sampling, or transporting cargo, and expelled naturally. A mathematical model is developed to optimize the mechanism's design. We demonstrate the capsule's multi-functional capabilities through successful drug delivery, sampling, and cargo transport experiments in a 3D printed maze. We also demonstrate capsule navigation in a stomach phantom. This unique mechanism can be adapted and integrated into a range of microrobotic devices, expanding their functionality and clinical utility.

Index Terms–medical robots, magnetic actuation, capsule, drug delivery, transmission mechanism.

I. INTRODUCTION

The gastrointestinal (GI) tract contains a large amount of bacteria (both beneficial and harmful), making it susceptible to many infectious diseases such as ulcers, bowel inflammation, colitis, mycobacterium tuberculosis, and various types of cancers [1]. Cancer-related cases are rapidly increasing worldwide, and more than one-fourth of these are related to the GI tract [2]. Since cancer cells can spread over time (metastasize) to other parts of the body, early diagnosis and treatment are necessary to improve GI health outcomes and manage the disease more effectively [3].

For treating such diseases, oral drug administration is a commonly used cost-effective technique; however, the drugs must withstand the acidic environment of the GI tract, which rapidly degrades their contents, reducing drug efficacy and bioavailability [4]. Targeted drug delivery addresses these challenges, while also reducing drug toxicity and enabling controlled drug diffusion [5].

Another challenge in treating GI tract disorders comes from the difficulty of current diagnosis methods. Conventional endoscopies currently being used are invasive, costly, and can cause discomfort to patients [6]. They are also unable to access deeper regions of the GI tract, and the absence of actively controlled components limits their application. Wireless capsule endoscopes, introduced in the early 2000s, offered a less invasive and more patient-friendly alternative as they are untethered and thus can be ingested easily through the mouth and expelled naturally from the body [7]. However, they face limitations as they are passive and still primarily confined to imaging the GI tract with limited applications in drug delivery and sampling.

Adding an active actuation mechanism to the capsule allows for its controlled movement within the body. These active mechanisms allow these capsules to perform a range of beneficial tasks, such as targeted drug delivery, microbiome, and tissue sampling. These extra functions enhance the usefulness and applicability of these capsules in diagnosing and treating GI tract disorders [8].

There has been a marked interest in integrating medical robots in surgical procedures within the body. Medical robotics research has rapidly advanced for various applications such as drug delivery [9], biopsy [10], [11], cargo transport [12], tissue cutting [13], and sampling [6]. These robots provide better precision, maneuverability, and access in performing many surgical procedures.

There are many different ways to actuate these robots, however, magnetic actuation has emerged as a popular choice for controlling these robots within the human body [10]. This is because magnetic fields are relatively safe for human use, can penetrate most materials, and can generate both forces and torques. This eliminates the need for onboard power systems and electronics such as batteries and motors, leading to the miniaturization of these robots. However, magnetically responsive materials need to be embedded within the robots for active control and to maneuver them inside a remote environment such as the human body [14].

Several wireless capsules have been designed over the last decade for drug delivery, imaging, or sampling. Shokrollahi et al. designed a magnetically actuated capsule for microbiome sampling consisting of two angled magnets aligned in opposite directions for opening using magnetic torque [6]. Lai et al. proposed a passively actuated capsule incorporating a pH-responsive hydrogel for triggering the sampling mechanism. They also integrated magnetic components inside the capsule for localizing it within the body [15]. Le et al. developed a capsule with soft magnetic components actuated using electromagnetic coils for drug delivery. This design used

the easy magnetization-demagnetization properties of paramagnetic materials (hysteresis curve) to apply the necessary forces and torques for precise control [16]. Finally, Sun et al. proposed a capsule with multi-functional capabilities for both drug delivery and sampling that was actuated by varying the frequency of magnetic fields. [17].

However, most of these capsules are limited to a single function or are passively actuated. Passively triggered mechanisms can have complications such as delayed response times due to the complex and variable pH environment of the GI tract and are more likely to be retained inside the body. Some multifunctional capsules exist, such as the capsule by Sun et al. [17]; however, this capsule is limited to drug delivery and sampling, while the ability to transport solid cargo is not shown. Therefore, a comprehensive system capable of performing multiple functions using a single mechanism can help in the treatment and monitoring of GI tract disorders by providing targeted therapy and real-time diagnostics with minimal patient discomfort. Moreover, it can also increase adoption by healthcare workers as they only need to be trained on one device to carry out various functions. Therefore, we aim to overcome some of the challenges of conventional capsules, which are typically limited to a single function with little or no active control. In this study, a magnetically actuated capsule is proposed, designed, manufactured, and tested. This capsule is capable of drug delivery, localized sampling, and cargo transport within the GI tract. The proposed capsule is navigated using a permanent magnet for wireless actuation. This mechanism enables targeted action without redesign or separate actuation mechanisms. This offers a flexible and scalable approach to gastrointestinal interventions.

The remainder of this paper is organized as follows: Section 2 discusses the design, the working of the mechanism, and the fabrication of the capsule. Section 3 details the mathematical model developed for optimizing the capsule mechanism using the energy-based and force-based approaches. Section 4 presents the experimental setup used and the results of the experimental evaluation. Section 5 summarizes the findings and presents future directions for the study.

II. METHODS

A. Design and mechanism of the capsule

The capsule presented in this work has a pill-shaped structure with two magnets on the outer surface. A spring-based mechanism is integrated into the capsule for opening and closing. This design means that the capsule can be navigated through the GI tract using either natural peristaltic movement or active gradient pulling using an external magnet. The schematic of the capsule can be seen in Fig. 1. The length of the capsule is 25 mm, and the diameter is 10 mm with a wall thickness of 1 mm. It can be separated into two parts: the top and bottom parts, with the top part also manufactured in two halves. The capsule relies on a transmission mechanism that consists of two cubic neodymium iron boron (NdFeB) magnets that are 2 mm in length, a spring, and a bar in the center to hold the spring with an upper and a lower stopper. The opening and closing mechanism relies on a magnet-spring

configuration. Magnets are affixed to opposite faces of the upper part of the capsule using an adhesive with identical poles facing each other. This configuration ensures that the magnetic moments are pointing in opposite directions. Therefore, when an external magnetic field is applied along the length of the capsule, both magnets rotate to align with it, causing the capsule to open. This allows the capsule to release the drug, take a sample, or grab cargo at the target location in the GI tract.

Inside the lower part of the capsule, a central bar holds the spring in place. The two stoppers are positioned to maintain the spring's orientation: the top stopper is fixed to the bar, while the bottom stopper can slide along the bar, allowing the spring to compress when pulled upwards. The lower stopper is connected to both magnets using a string that remains under tension while connected. This ensures that the capsule remains securely closed as it travels through the GI tract and only opens when activated by the external magnetic field.
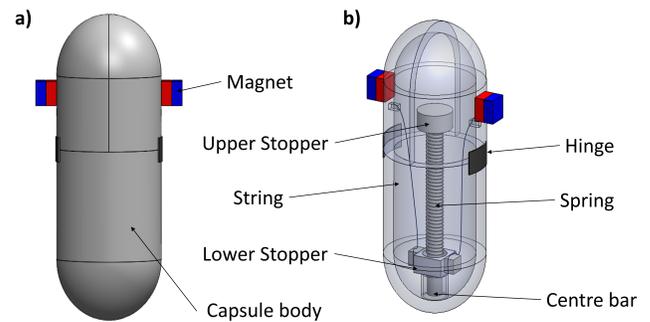

Fig. 1. Schematic of the capsule showing **a)** front view **b)** internal view showing the mechanism.

B. Working principle of the capsule mechanism

The capsule can be ingested orally through the mouth and traverses the GI tract to reach the stomach as shown in Fig. 2a). It is actively steered toward the target site using magnetic fields from outside the body. It is capable of multiple functions inside the GI tract, such as drug delivery, sampling, or cargo transport, as shown in Fig. 2b) and 2c) respectively. When it reaches the desired location, a magnetic field is applied along the longitudinal axis of the capsule to trigger the opening mechanism. The magnetic moments of the internal magnets, initially oriented perpendicular to the field direction, attempt to align with the field when an external field is applied. As these magnets are attached to the upper part of the capsule, the resulting torque causes the capsule to open as depicted in Fig. 2d). At the same time, the lower stopper slides upward along the central bar, compressing the spring and storing elastic potential energy. Drug release or sample and cargo collection occurs while the capsule is open. The compressed spring returns to its original state when the external magnetic field is removed, releasing the stored potential energy and closing the capsule. A magnetic field in the opposite direction can also be applied to facilitate the closure of the capsule.
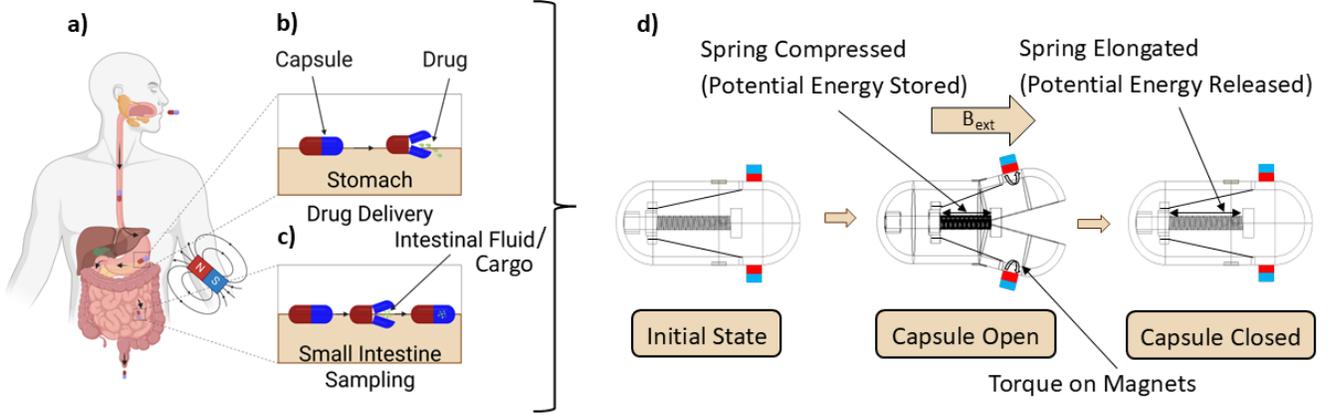
Fig. 2. Function, application and working principle of the capsule are shown. **a)** Schematic of the human GI tract and the ingestible capsule. This figure was generated using Biorender. **b)** Schematic showing the drug release process. **c)** Schematic showing the intestinal fluid sampling process. **d)** Schematic showing the working principle of the capsule mechanism.

C. Fabrication

The capsule's upper and lower parts, stoppers, and central bar are manufactured using a 3D printer (Prusa MK4) extruding Polylactic Acid (PLA). First, the strings (0.2 mm, Trilene, Pure Fishing Inc.) are attached to both ends of the lower stopper by tying a knot around the protruded part of the stopper. Super Glue (The Gorilla Glue Company) is used to attach the strings and ensure that the strings remain taut and do not slacken. Next, the spring (k= 74 N/m, CI 008C 09 S, Lee Spring) is inserted along the central bar, with one end resting against the upper stopper. The lower stopper is then inserted, which can freely move along the bar. This setup holds the spring between the two stoppers. The central bar, supporting the spring and stoppers, is subsequently inserted and glued securely into the channel located in the center of the lower part of the capsule. Two cube NdFeB magnets (2 mm, C0020, Supermagnetman) are then glued to the upper portion of the capsule, with the north pole of each magnet attached to the capsule face as shown in Fig. 3 and the south pole facing outward. The other end of the string is threaded through a hole located just below the magnet in the upper part of the capsule. The two halves of the upper part of the capsule are concentrically placed on the lower part and secured with adhesive tape. The strings are pulled tight from the outside and adhered to the capsule. Any excess string is later trimmed off using a pair of scissors. To maintain uniform tension in the strings, a 3D-printed setup was designed. Strings were pulled over a cylindrical roller. Equal calibrated weights of 20 g each were hung at the end of the string. This ensures both strings are tightened uniformly. An adhesive tape is carefully cut using a box cutter to create a hinge that allows the capsule to open and close as needed. Adhesive tape is used as a hinge in this proof-of-concept study, however, the hinge design is critical, and alternative designs may be explored to further enhance the hinge's performance. The capsule is designed to fit within commercially available gelatin shells that meet the size requirements of #000 capsules. Therefore, the capsule can also be covered with a gelatinous layer before swallowing.

This will allow easy swallowing of the capsule and will ensure that the drug inside the capsule is safe until it reaches the target site in the GI tract. As the gelatin shell dissolves in the target region, the robotic capsule can be used to perform its intended functions, such as drug delivery or sampling, or cargo transport.
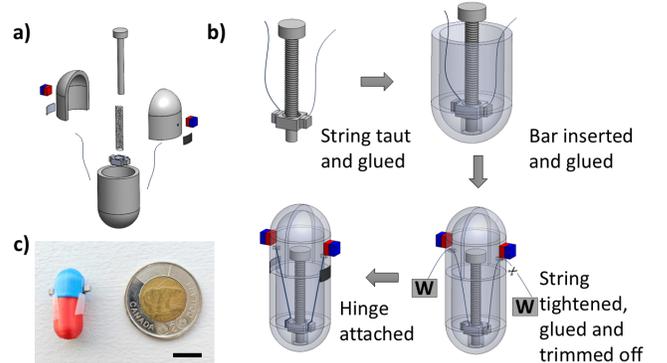

Fig. 3. Schematic of **a)** components of the capsule in exploded view. **b)** Process of capsule assembly. **c)** Fabricated capsule (Scale bar: 10 mm).

III. ANALYTICAL MODEL

To model the behavior of the magnet-spring mechanism and optimize the design of the capsule, two different models were developed and analyzed: 1) the energy-based model and 2) the force-based model. The analytical models developed here are used to characterize the design parameters of the capsule, such as the spring constant (k), string tension, and magnet size.

A. Energy based approach

Fabrication of the capsule imparts an initial tension in the string as shown in Fig. 3b). Assuming negligible friction between the cylinders through which the string passes and the string, the tension in the string, T, is given by:

$$T = W \times g \tag{1}$$

where W is the mass of the weights used to maintain the tension in the strings and g is the acceleration due to gravity.

The magnets on the capsule can be modeled as magnetic dipoles with magnetic moments $\mathbf{m_1}$ and $\mathbf{m_2}$ as shown in Fig. 4. When a magnetic dipole $\mathbf{m}$ is placed in a magnetic field $\mathbf{B}$, it experiences a torque $\boldsymbol{\tau}$ which causes the magnets to rotate and align with the external magnetic field:

$$\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B} \tag{2}$$

The work done dW in rotating the magnetic dipole by an infinitesimal angle $d\phi$ is

$$dW = \boldsymbol{\tau} \cdot d\boldsymbol{\phi} \tag{3}$$

The magnetic potential energy U_m is the negative of the work done by the torque in bringing the dipole from a reference orientation to the current orientation:

$$U_m = -mB \cos\phi \tag{4}$$

where ϕ is an angle between the external magnetic field and the magnetic moment. In vector form, this potential energy is:

$$U_m = -\mathbf{m} \cdot \mathbf{B} \tag{5}$$

For magnets $\mathbf{m_1}$ and $\mathbf{m_2}$ and based on the assumption that the magnet rotation is symmetric, the potential energy can be summarized as:

$$U_m(\phi) = -(m_1 + m_2)B \cos\phi \tag{6}$$

When an external magnetic field is applied along the length of the capsule, the initial angle ϕ is 90°. The torque generated acts on the magnets, resulting in the opening of the capsule and compression of the spring at the same time. Therefore, the work done on the spring is stored as elastic potential energy (U_s) in the spring as:

$$U_s = \frac{1}{2}kx^2 \tag{7}$$

where x is the compression of the spring.

As the magnet rotates to align with the external magnetic field, there is a transfer of energy to the spring which starts to store it as elastic potential energy as it compresses. Therefore, the law of energy conservation gives:

$$dU_m(\phi) = dU_s(x) \tag{8}$$

It should be noted that friction due to the movement of the stopper along the bar and the motion of the hinge have been neglected.

The deflection of the spring due to the initial tension is given by the following force balance equation as:

$$x_i = \frac{2T\cos\theta}{k} \tag{9}$$

where θ is the initial angle of the string with respect to the center bar as shown in Fig 4 a).

Since the spring is slightly compressed due to string tension in its initial position, the minimum magnetic field required to open the capsule is given by:

$$B_{min} = \frac{kx_i^2}{2(m_1 + m_2)} \tag{10}$$

Now, the relationship between the applied magnetic field B, and the magnet rotation angle ϕ can be derived as:

$$(m_1 + m_2)B(1 - \cos\phi) = \frac{1}{2}kx^2 \tag{11}$$

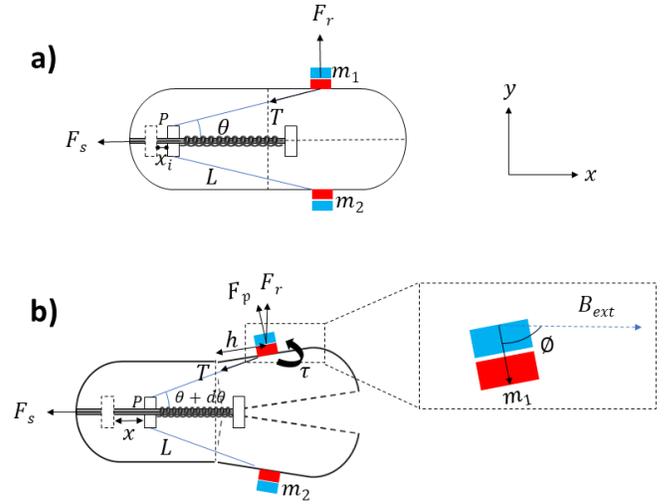### B. Force based approach

Fig. 4. Schematic showing the physics-based modelling of the capsule mechanism when **a)** no external field is acting, **b)** external field is applied.

Since the string is connected to the magnet from one end and to the stopper from the other end, this creates tension in the string. Assuming perfect parallelization of the string and extrapolating the mechanism to a 2D plane, the tension in each string can be modeled in vector form as:

$$\mathbf{T} = T_x\mathbf{i} + T_y\mathbf{j} \tag{12}$$

When the magnetic field is applied, the spring starts to compress. The force due to the linear spring compression is given by Hooke's Law:

$$\mathbf{F_s} = -kx\mathbf{i} \tag{13}$$

The magnetic interaction force exerted by dipole 1 on dipole 2 with the respective magnetic moments $\mathbf{m_1}$ and $\mathbf{m_2}$ is:

$$\mathbf{F_{12}} = \frac{3\mu_0}{4\pi r^5}\left[(\mathbf{m_1} \cdot \mathbf{r_{12}})\mathbf{m_2} + (\mathbf{m_2} \cdot \mathbf{r_{12}})\mathbf{m_1} \right. \tag{14}$$
$$\left. + (\mathbf{m_1} \cdot \mathbf{m_2})\mathbf{r_{12}} - \frac{5(\mathbf{m_1} \cdot \mathbf{r_{12}})(\mathbf{m_2} \cdot \mathbf{r_{12}})}{r^2}\mathbf{r_{12}}\right]$$

where $\mathbf{r_{12}}$ is a vector from $\mathbf{m_1}$ to $\mathbf{m_2}$ and r is the magnitude of $\mathbf{r_{12}}$.

In this case, the two magnetic dipoles with magnetic moments $\mathbf{m_1}$ and $\mathbf{m_2}$ are aligned along the same axis but in opposite directions; therefore, a repulsion force $\mathbf{F_r}$ between them can be simplified as:

$$\mathbf{F_r} = \frac{3\mu_0 m_1 m_2}{2\pi r^4}\mathbf{j} \tag{15}$$

For the capsule to remain closed in the absence of a magnetic field, all forces should be in equilibrium:

$$\sum F_x = 2T_x - F_s = 0 \tag{16}$$

$$\sum F_y = T_y - F_r = 0 \tag{17}$$

When an external magnetic field is applied, it rotates the upper faces of the capsule about the hinge. This torque can be translated to a pseudo-mechanical force $\mathbf{F_p}$ for use in our model:

$$\mathbf{F_p} = F_{px}\mathbf{i} + F_{py}\mathbf{j} \tag{18}$$

As shown in Eq. (2), when a magnetic dipole $\mathbf{m}$ is placed in a magnetic field $\mathbf{B}$, it experiences a torque $\boldsymbol{\tau}$. Assuming $\mathbf{F_p}$ is perpendicular to the surface of upper part of the capsule at all times, the relationship between F_p and the magnetic torque can be derived as:

$$\tau = mB\sin\phi = F_p h \tag{19}$$

where h is the distance from the hinge to the magnet.

Therefore, B_{min} can be derived from the balance of forces when the capsule is closed and is given by:

$$B_{min} = \frac{kx_i h\tan\theta}{2m_1} \tag{20}$$

The relationship between the applied magnetic field B, and the magnet rotating angle ϕ can also be derived as:

$$2m_1 B \sin^2\phi \cos(\theta + d\theta) = kxh\sin(\theta + d\theta) \tag{21}$$

IV. RESULTS

A. Experimental setup

Experiments are completed using a 1.5-inch cube permanent magnet for actuation. A hand-held permanent magnet is translated to move the capsule through the maze. The robotic arm is used to navigate the capsule in the stomach phantom. When the permanent magnet is brought closer to the capsule axially, the opening mechanism is triggered once the magnetic field strength overcomes the resistive force of the spring. Once the capsule has opened, the actuating magnet is slowly pulled back, allowing the capsule to close as a result of the spring returning to its original position.

B. Capsule opening characterization

The opening angle of the capsule is measured by placing the capsule on a cardboard platform. A ruler is placed on the board for precise measurement. The 1-inch cube NdFeB magnet is used to trigger the capsule mechanism, and the magnetic field at the capsule's location is recorded using a F71 Teslameter (Lakeshore Cryotronics). Images are captured for different values of magnetic flux density as an actuating magnet is brought closer to the capsule. The images are then analyzed using MATLAB to determine the opening angle of the capsule faces. This data is plotted for the magnetic flux density and the opening angle of the capsule along with the predicted data using the force and energy based models, as
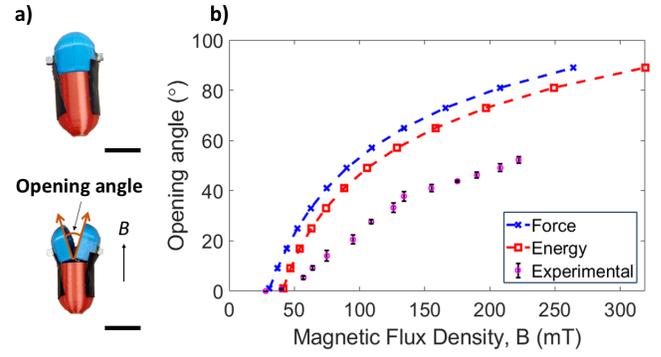

Fig. 5. a) Capsule in closed and open states, where the opening angle is shown. b) The measured opening angle (°) as a function of magnetic field, B (mT) is plotted as well as theoretical values from the energy and force models (Error bars represent the SDs for 5 measurements). (Scale bar: 10 mm)
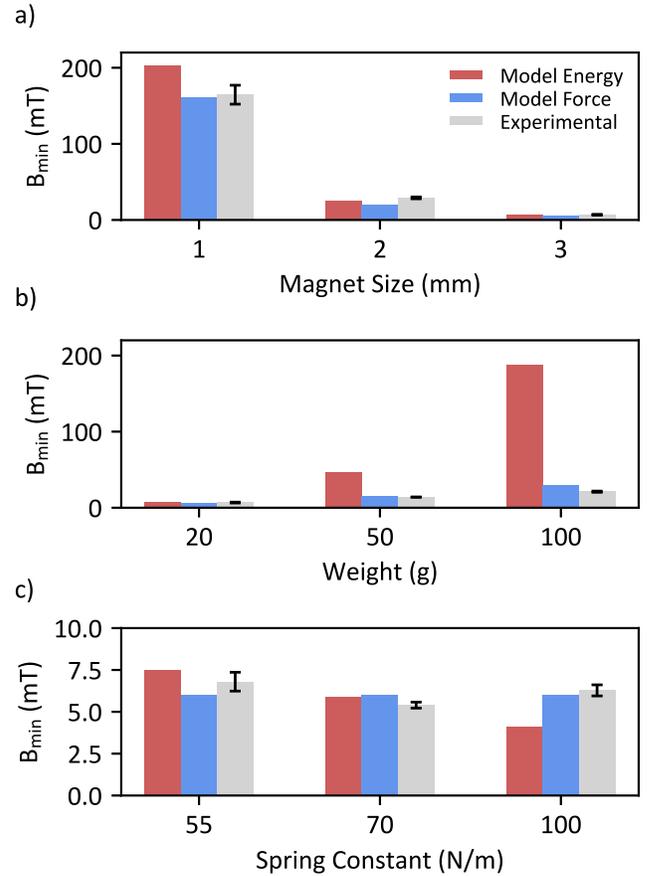

Fig. 6. The graph shows the minimum field required to open the capsule. **a)** for varying magnet sizes. **b)** for varying tension/weight. **c)** for varying spring constant (Error bars represent the SDs for 5 measurements).

shown in Fig. 5. The predicted data shows a similar trend to the experimental; however, there is some deviation between the actual and predicted results. This can primarily be attributed to the friction present between the bar and stopper, which is not included in our current model.
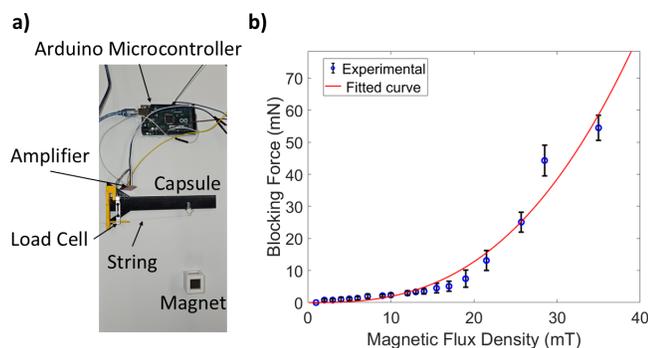
Fig. 7. a) Experimental setup for measuring the capsule's blocking force. b) The capsule's blocking force as a function of magnetic field strength, B (mT) is plotted along with a curve fit (Error bars represent the SDs for 5 measurements).

C. Minimum magnetic field characterization

To characterize the minimum magnetic field required to open the capsule, capsules with different magnet sizes, spring constants, and string tensions were manufactured. The magnetic field required to open the capsule was measured using a F71 Teslameter (Lakeshore Cryotronics), and the values are compared with the mathematical model developed. Capsules with 3 different magnet sizes (1 mm, 2 mm, and 3 mm) were fabricated, while keeping the spring constant (k = 55 N/m) and a uniform string tension (with 20 g weights) constant. The plot showing the theoretical and experimental values is shown in Fig. 6a). From the graph it can be observed that as the magnet size on the capsule is increased, the magnetic field required to open the capsule is decreased. This can be explained as follows: increasing the magnet size results in a higher magnetic moment due to a larger volume of magnetic material.

Additionally, capsules with varying string tension were manufactured using different weights during fabrication while keeping the spring constant (k = 55 N/m) and magnet size (3 mm) unchanged. The plot in Fig. 6b) shows the magnetic flux density required increases slightly as the tension in the strings is increased. This can be explained as follows: an increase in tension in the strings results in greater compression of the spring. As a result, the torque required to compress the spring further is also increased, resulting in higher fields required to open the capsule. However, the energy model shows a significant deviation in estimating the magnetic field required for capsule actuation. The model assumes that increasing the pre-tension in the strings leads to greater pre-compression of the spring, therefore requiring a stronger magnetic field to further compress the spring and trigger capsule opening. In practice, this assumption does not fully hold, as some of the observed tension maybe lost during the fabrication process. As a result, the model tends to overestimate the magnetic field needed to actuate the capsule. Lastly, capsules with varying spring constants were fabricated while keeping the magnet size (3 mm) and the tension in the string (20 g) constant. As can be seen from the plot in Fig. 6 c), the magnetic field required to open the capsule sees a minimal change. This indicates

that the variation in the spring constant is less important than changes in magnet size. As the magnetic field strength decays with distance, capsules that require smaller fields to open can be used more easily in patients, however, further studies must be conducted to ensure that peristaltic forces within the body do not prematurely open the capsule as it navigates the GI tract.

D. Blocking force measurement

To measure the blocking force of the capsule against the applied magnetic field, a load cell (SEN-14727, Sparkfun electronics) and the capsule are mounted on a fixed platform. One face of the capsule was connected directly to the load cell using a string. An actuating 1-inch permanent magnet is used to generate a magnetic field to open the capsule. Since the capsule is directly connected to the load cell using a string, the capsule does not physically open, but the force generated is recorded by a load cell using a microcontroller (Arduino MEGA 2560 R3) and amplifier (SEN-13879, Sparkfun electronics) circuit used to amplify the force signals. The force measurement setup is shown in Fig. 7a). The measured force of the capsule is plotted against the magnetic flux density with a fitted curve as shown in Fig. 7b).

E. Drug delivery experiments

Drug delivery using the capsule is shown by moving the capsule through a 3D printed maze as seen in Fig. 8 and successfully delivering the red powder at the target location. The maze was 3D printed and consisted of an S-shaped path with a reservoir mimicking the tortuous paths of the GI tract. The reservoir is located at the end of the maze and is filled with water. Using the permanent magnet, the capsule was moved through the maze, demonstrating the controllability of the capsule inside a remote environment. The capsule is navigated in the maze using a non-uniform field to generate a magnetic force by translating a handheld magnet. To ensure the capsule does not open while moving, a magnetic field lower than the field required to trigger the capsule is used. The actuating magnet was brought closer to the capsule to increase the magnetic field strength to open the capsule. More sophisticated actuation systems such as Navion [18] can be used to provide more precise control. The powder was successfully delivered to the reservoir by triggering the capsule mechanism using a 1.5-inch permanent magnet to open the capsule. Once the drug was released, the permanent magnet was slowly moved back, and the capsule was automatically closed with the release of the potential energy stored in the spring as a result of compression.

F. Sampling and Cargo transport experiments

To show the sampling action of the capsule, the maze is modified by adding a reservoir midway along the path of the capsule. The reservoir at the end of the maze is filled with clear water, and the reservoir midway is filled with a red food dye dispersed in water. The capsule is guided through the maze using a permanent magnet. Upon reaching the dye-dispersed location, the mechanism is activated by applying
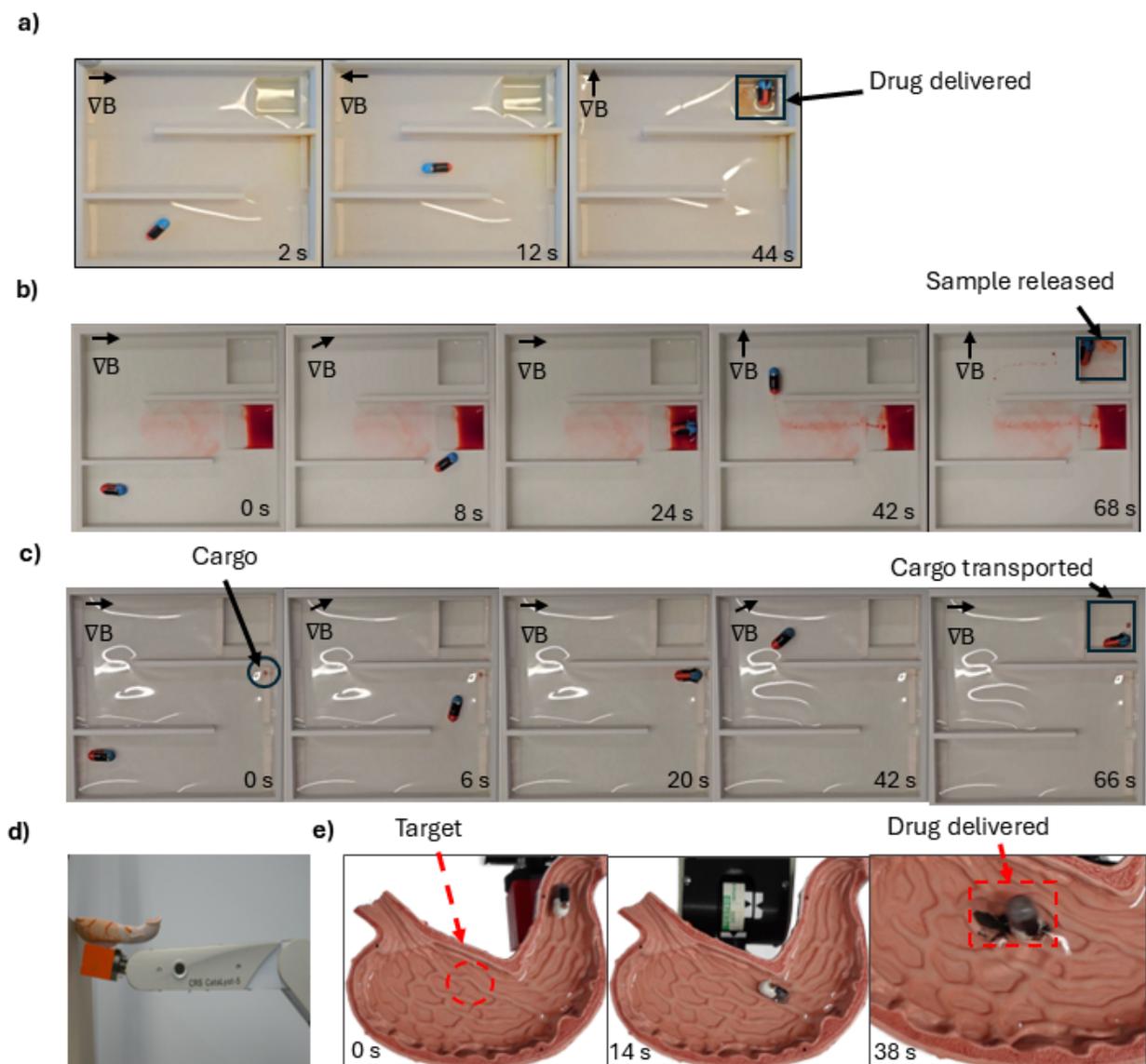
Fig. 8. Experiments using the capsule to show a) successful drug delivery by actuating the capsule to the reservoir and then opening, b) successful sample collection and delivery to the reservoir, c) successful cargo collection and transport to the reservoir. d) Experimental setup of a magnetic actuation system for showing e) drug delivery in the stomach phantom.

an external magnetic field using the permanent magnet. The sample was collected by opening the capsule. The capsule is then further navigated through the maze to the reservoir. At the reservoir, the mechanism is triggered again, and the sample is successfully delivered. This is confirmed by observing the color of the water, which indicates successful sample collection and transfer. Similarly, for cargo transport, the same maze used for drug delivery was used again, and a solid cargo made of agar gel was hung through a nitinol wire attached to the wall of the maze. The capsule was again moved from the start point and opened to collect the cargo. After collecting the cargo, it was transported by moving the capsule to the reservoir and opening it to release the collected cargo.

G. In vitro demonstration in the stomach phantom

To demonstrate the capsule's feasibility in navigating the tortuous and complex gastric folds of the stomach, experiments in a stomach phantom model were performed. First, the stomach was filled with water, and the capsule was placed on one side of the stomach phantom. The capsule was navigated using a 1.5-inch cube permanent magnet (K&J Magnetics) mounted on a 5-DOF robotic arm (CRS Catalyst-5, Thermo Scientific). After navigating to the target site, the magnet was rotated and brought closer to the capsule to increase the magnetic field to open the capsule, which then released the black powder mimicking drug. This can be verified by looking at the change in color of the water at the target site.

V. CONCLUSIONS

In this study, we present a novel capsule mechanism capable of drug delivery, microbiome sampling, and cargo transport within the GI tract. Experimental results show the precise control of the capsule's movement through a maze using magnetic actuation, effective drug delivery at the target site,

successful liquid sampling, and solid cargo transport. The design presented here serves as a proof-of-concept and can be further improved by the choice of materials such as biocompatible resins and alternative hinge designs.

Future work will involve developing seals and performing sealing tests to ensure that the sample is not contaminated along the route. Testing will be conducted *ex vivo* and *in vivo* to simulate the complex environment of the real gastrointestinal tract (such as mucus, peristalsis, pH changes). Furthermore, tests will be conducted on various capsules to show reproducibility and that they can withstand peristaltic pressure and do not open prematurely. Additionally, cytotoxicity tests and fatigue tests on the capsule mechanism needs to be conducted to ensure biocompatibility and durability of the capsule inside the body. The modeling of the capsule mechanism can also be improved by using a 2-bar multi-body formulation and adding friction effects to more accurately mimic the physical setup. Finally, the mechanism presented here can generate large forces, which need to be quantified and tested for tissue puncturing. This would allow future versions of the capsule to be used for biopsies.

ACKNOWLEDGMENT

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