Origami Inspired Design for Capsule Endoscope to Retrograde Using Intestinal Peristalsis

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***Abstract*—Capsule endoscopy has gained a lot of attention in the medical field in the recent past as an effective way of investigating unusual symptoms experienced in places such as esophagus, stomach, small intestine and colon. However, motion control of the capsule endoscope is challenging and often requires a power source and miniature actuators. To address these issues, we present a novel origami inspired structure as an attachment to the capsule endoscope. The proposed origami structure utilizes the wave generated by peristalsis of the intestine to move it forward and backward. When the origami structure is folded, the capsule endoscope is propelled forward by intestinal peristalsis. When the origami structure is unfolded, the intestinal peristalsis squeezes the origami structure to drive the capsule endoscope to move in the opposite direction. Therefore, folding and unfolding of the proposed origami structure would allow to control the movement direction of the capsule endoscope. In this letter, we present the design, simulations and experimental validation of the proposed origami structure.**

***Index Terms*—Capsule endoscope, medical robots, origami robots, soft robots.**

I. Introduction

INVESTIGATING unusual symptoms experienced in the esophagus, stomach, small intestine, the colon are important for detection of early diseases such as stomach cancers, ulcers etc. While endoscopy is the mostly used procedure for scanning the patient who are suffering from such unusual symptoms, the endoscopy procedure is very invasive. It involves the insertion of an endoscope through a patient's mouth and it contains a risk of damaging or lesions in the subjected organs. Alternatively, the capsule endoscopy [1] technology has demonstrated to be a powerful tool in the diagnosis and management of small bowel disorders since its introduction in 2001 [2]. The recent developments and applications of the capsule endoscope has paved the way to address many of the common issues seen in the conventional endoscope.

Capsule endoscope is a common equipment used for intestinal lesion inspection [3]. However, due to the constrained environment in the intestine, the control and movement of the capsule endoscope is very challenging [4]. The current mainstream capsule endoscope has no movement device and can only be moved forward by the intestine. This lack of controllability in position and direction leads to inefficiency in pathological screening [5]. At present, there are some related research on capsule endoscopes that can be propelled autonomously, such as using small propellers [6], vibratory motor [7], mechanical legs [8] and other methods to move [9]–[12]. However, these movement devices consume energy, and because the capsule endoscope is small in size, about 13 mm in diameter [5], the battery size of the capsule endoscope is limited, and therefore the energy is relatively limited [13]. At present, there are also Magnetically Guided Capsule Endoscopy (MGCE) systems. This technology controls the movement of the capsule endoscope using a magnet controlled outside the body [14]–[16]. However, the equipment of this type of technology can only be used for gastric examinations. Also, it is large in size, and some use industrial-grade robotic arms, which can cause injury to patients if they are not properly operated [17].

On the other hand, peristalsis refers to the phenomenon that the smooth muscles in the intestine contract along the channel wall in order to push the chyme to move forward in the direction of the wave [18]. The wave speed of peristaltic waves in the small intestine can reach 1 cm/s [19], and 15 to 18 peristaltic waves can be generated per minute [20], which is a very rich source of power. The capsule endoscope can be pushed in the direction of peristalsis by peristaltic waves, but cannot move in the opposite direction. Given the necessity of having a controllable capsule endoscope, this motivated us to address the question whether we also let the peristaltic waves push the capsule endoscope in the opposite direction, so as to achieve the purpose of making the position of the capsule endoscope in the intestine controllable.

In this letter, we present an origami inspired structure that can be pushed back by peristaltic waves in a peristaltic pipe as an attachment to the capsule endoscope. The conceptual overview of our proposed system is shown in Fig. 1. The structure is composed of several trapezoidal sheet-like substructures connected in series and made of soft TPU material. When the origami structure is folded, the capsule endoscope is propelled forward by intestinal peristalsis. When the origami structure is unfolded, the intestinal peristalsis squeezes the origami structure to drive the capsule endoscope to move in the opposite direction.

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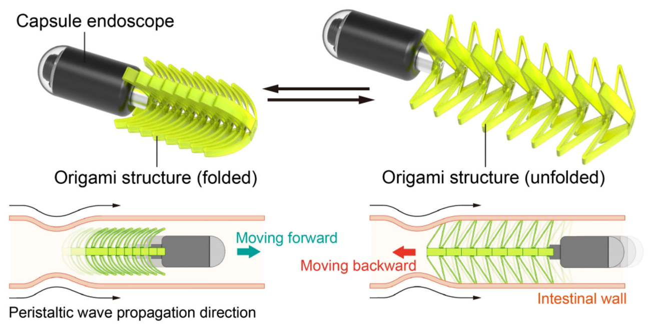

Fig. 1. Conceptual overview of the proposed system. When the origami structure is folded, the capsule endoscope is propelled forward by intestinal peristalsis. When the origami structure is unfolded, the intestinal peristalsis squeezes the origami structure to drive the capsule endoscope to move in the opposite direction. Therefore, folding and unfolding of the proposed origami structure would allow to control the movement direction of the capsule endoscope.

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The rest of the letter is structured as follows. The method section presents the design of the proposed origami structure for the capsule robot together with a simulation study. Experimental validation of the proposed origami structure together with a discussion is presented in the Experiments and Results section. Finally, the letter concludes with potential future directions.

II. Methods

Initial inspiration for our proposed approach was taken from an inchworm robot [21] design. When this kind of robot stretches and stretches its body repeatedly, the anisotropic friction material on the surface will cause the robot to move in a specific direction. But the expansion and contraction of this robot needs to be driven by its own energy. In order not to use energy, we thought of using the peristalsis of the intestine to make the robot passively extend and retract. Due to the small size of the capsule endoscope, in order to achieve this function, compared to the mechanical structure, the origami structure may be more feasible. Because it may be simpler to make an origami structure on a small scale than mechanically, and the origami structure can be relatively soft and will not harm the human body. There have been some examples of applying origami structure to the capsule endoscope to complete different tasks in the stomach, such as diagnosis, wound repair or injection [22], [23]. So we proposed a kind of flexible origami structure (as shown in the Fig. 2). This structure has many angles inclined in one direction which constrains the movement of the capsule robot along the intestine. This is equivalent to an anisotropic friction effect. In addition, our origami inspired capsule robot contracts along the major axis when it is squeezed in the perpendicular direction and restores the original shape when it is released. This is equivalent to having a negative Poisson ratio. (The negative Poisson's ratio structure has a special shape, that is, when the structure is squeezed in one direction, it will also shrink in other directions [24].) Therefore, repeated squeezing and releasing due to peristaltic waves along the intestine helps the origami inspired capsule robot to passively move along the intestine.

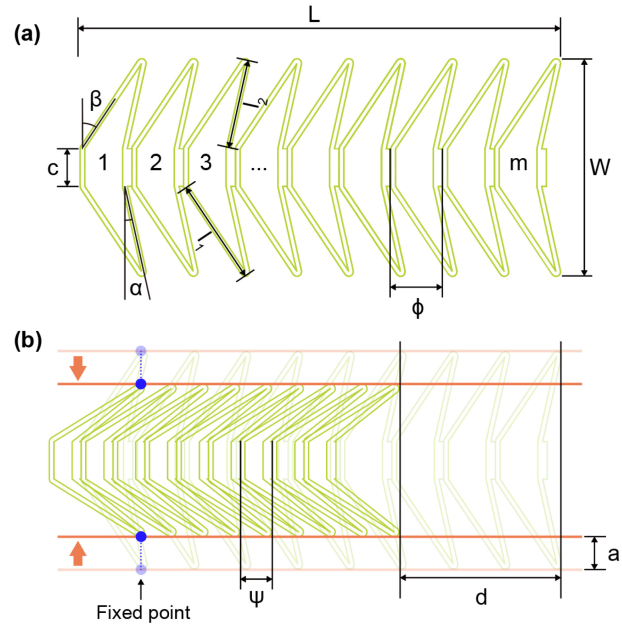

Fig. 2. Detailed design of the proposed origami structure. **(a)** The state of the origami structure when it is not squeezed. **(b)** The origami structure is completely squeezed by intestinal peristalsis.

A. Proposed Design

We designed an origami structure composed of crescent-shaped films arranged. When the structure is squeezed from both sides, the longitudinal direction of the structure will shrink at the same time. When this structure is sucked on two belts. Because the crescent-shaped tip has an included angle with the belt, it has the same special-shaped friction properties as snake scales. When squeezing the belt, the rear end of the structure will shrink as before. When the squeezing disappears, the structure will expand again and move forward for a certain distance.

Fig. 2(a) shows a detailed design of the proposed origami structure. The overall width of the structure is W and the length is L. The structure consists of n crescent-shaped substructures. The width of the middle connecting part of the substructure is c. The angle between the long side of the substructure and the longitudinal axis is β, and the angle between the short side of the substructure and the longitudinal axis is α. The length of the long side of the crescent structure is l_1, and the length of the short side is l_2. The distance between the substructures is ϕ.

In order to make the origami structure move as far as possible when it is squeezed, we obtained the best values of β, α and c through kinematic analysis. Fig. 2(b) shows that we have simplified the situation where the origami structure is squeezed by the intestine. The diameter of the intestine is equal to the width of the origami structure, which is W. When the structure is squeezed, the entire structure will shrink to the left with the blue contact points at the left end as the fixed points. Intestinal peristalsis is simplified as the entire intestine shrinks inward by a distance a. At this time, the adjacent distance of the substructure on the origami structure is squeezed to ψ. The distance that a single substructure shrinks is d_0. The distance that the tail of the entire origami structure moves forward is d. The larger the value of d, the stronger the mobility of the structure.

First, we calculated the length of the long and short sides of the crescent structure:

$$l_1 \cos\beta = \frac{(W-c)}{2}$$
$$l_1 = \frac{(W-c)}{2\cos\beta} \tag{1}$$
$$l_2 \cos\alpha = \frac{(W-c)}{2}$$
$$l_2 = \frac{(W-c)}{2\cos\alpha} \tag{2}$$

Then, the spacing between the substructures is calculated:

$$\phi = l_1 \sin\beta - l_2 \sin\alpha$$
$$= \left(\frac{W-c}{2}\right)(\tan\beta - \tan\alpha) \tag{3}$$

We calculated the spacing between the substructures when the origami structure was squeezed:

$$\psi = \sqrt{l_1^2 - \left(\frac{(W-c)}{2} - a\right)^2} - \sqrt{l_2^2 - \left(\frac{(W-c)}{2} - a\right)^2} \tag{4}$$

Hence, we obtained the relationship between the displacement distance of a single substructure (d_0) and c, β, α:

$$d_0 = \phi - \psi$$
$$= \left(\frac{W-c}{2}\right)(\tan\beta - \tan\alpha)$$
$$- \sqrt{\left(\frac{(W-c)}{2}\right)^2 \sec^2\beta - \left(\frac{(W-c)}{2} - a\right)^2}$$
$$+ \sqrt{\left(\frac{(W-c)}{2}\right)^2 \sec^2\alpha - \left(\frac{(W-c)}{2} - a\right)^2} \tag{5}$$

Given known c and β, we can find the best α to maximise d_0 give by:

$$\frac{\partial d_0}{\partial \alpha} = 0 \sec^2\alpha \left[1 - \left(2 - \sec^2\alpha\right)^2 \tan^2\alpha\right]$$
$$= \left(\frac{2}{W-c}\right)^2 \left(\left(\frac{2}{W-c}\right) - a\right)^2 \tag{6}$$

The total displacement of the entire structure (d) depends on the number of substructures (m):

$$d = m d_0 \tag{7}$$

After conducting several pre-experiments and iterations, we summarized the following design requirements for the structure:

- α should be around 13°. If the angle is too large, the angle between the crescent structure and the intestine will be too small, and the forward deformation during the intestinal squeezing process will decrease. If the angle is too small will cause the substructure to deform backward when the short side of the crescent is squeezed by the intestine.
- β should be around 34°. If the angle is too small, the substructure will be too narrow and the forward deformation will be smaller. If the angle is too large, the spacing between the sub-structures will increase, and at the same time the number of sub-structures squeezed by a peristaltic wave will decrease, resulting in less total displacement.
- W is roughly equivalent to the diameter of the intestine. If the width W is too small, it will not be stuck on the intestine, and if it is too large, it will slow down the movement speed.
- The value of c should be $1/5$ of M. When c is too short, the structure will be easily bent, resulting in lower moving efficiency. When c is too long, the forward deformation of the substructure will be greatly reduced.
- The number m of substructures should be about 9. If it is too small, the origami structure will have too few contact points with the intestine, making it difficult to move. If the number is too large, the friction will increase and the movement efficiency will decrease.

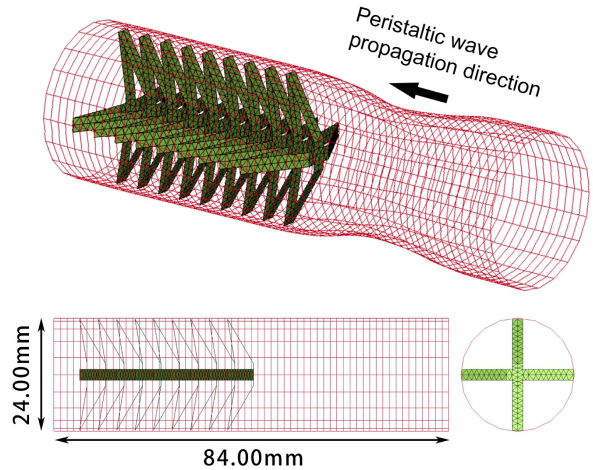

Fig. 3. Overall simulation set-up. The origami structure was placed on the left side in the intestine, and the peristaltic wave moved from the right to the left.

Based on these requirements, we designed a set of structures and tested in pre-experiments and found that a model with $c/M = 1/5$, $\alpha = 12.53°$, $\beta = 33.69°$ and $m = 9$ works best. Then we used that model in simulations and experiments.

B. Simulations

We used LS-DYNA software to conduct a preliminary simulation of the structure's movement in the small intestine. The set-up of the simulation is shown in Fig. 3. The intestine model is a tube with a diameter of 24.00 mm [18], a length of 84.00 mm, and a thickness of 2.40 mm [25]. Its density is 1 g/mm^3 [26], Young's modulus is 1 MPa [27] and viscosity is 5.35 MPa· s [26]. In order to make the origami structure fit in the tubular intestine, we changed the structure to a cross shape, the diameter of which is the same as the inner diameter of the intestine. The width of the crescent structure is changed to 2.00 mm, and the thickness is 0.80 mm. The material is elastic plastic, where density is 1.4 g/mm^3, the shear modulus and bulk modulus are 0.6 MPa, and 2.0 GPa respectively. We divided the intestine model into 10 segments with a length of 8.4 mm. And at 1 s intervals, from the right end to the left, they were given 3 seconds of peristaltic pressure perpendicular to the surface of the intestine and directed to the inside of the intestine. The pressure linearly increases from 0 to maximum value in 1.5 seconds, and then linearly decreases from maximum value of to 0 in 1.5 seconds. The maximum value is the intestinal peristalsis pressure value. In this way, a relatively consistent peristaltic wave can be formed, which is similar to the actual small intestine peristaltic wave velocity [19]. At the same time, 4000 Pa is perpendicular to the surface of the intestine [28], and the pressure directed to the outside of the intestine is applied to the entire intestine as the internal pressure of the intestine to prevent it from collapsing during the peristaltic process.

We speculated that the speed of the origami structure in the intestine may be related to the friction between the intestine and the structure and the pressure of the intestinal peristalsis, so two sets of simulation experiments were carried out. Studies have shown that the coefficient of friction between the capsule endoscope and the intestine is between 0.08 and 0.20 [25].

In order to study the relationship between the speed of the origami structure and friction coefficient, we placed the origami structure on the left side in the intestine, with the head facing the right side, and then let the intestine begin to perform continuous peristalsis from the far right end to the far left end. We record the displacement process of the origami structure when the friction coefficient between the intestine and the origami structure changes from 0.08, 0.085, 0.09,..., 0.20 under the condition of the peristaltic pressure of 7000 Pa within 20 seconds after the start of the peristalsis.

To explore the relationship between the moving speed of the origami structure and the pressure of the intestinal peristalsis, we also placed the origami structure on the left side in the intestine, with the head facing to the right, and then let the intestine begin to move continuously from the right end to the left end. We record the displacement process of the origami structure when the intestinal peristaltic pressure changes from 3000 Pa, 3400 Pa, 3800 Pa,..., 7000 Pa when the friction coefficient between the intestine and the origami structure is 0.15 within 20 seconds after the start of the peristalsis. Since it is difficult to find the measured value of intestinal peristalsis pressure, we determined the pressure range of intestinal peristalsis through simulations. We found that from 3000 Pa, the intestines will start to indent slightly, and when the pressure is above 7000 Pa, the intestinal wall will be severely shrunk and deformed. Accordingly, we chose to conduct experiments in the range of 3000 Pa to 7000 Pa, which is theoretically close to the real peristalsis pressure.

C. Simulation Result

Fig. 4(a) shows the relationship between friction coefficient, time and displacement. It can be seen that the displacement of the origami structure under each friction coefficient is about 14 mm within 20 seconds, and there is no obvious correlation between the displacement speed and the friction coefficient of the origami structure.

Fig. 4(b) depicts the relationship between intestinal peristalsis pressure, time and displacement. It can be seen that when the intestinal peristalsis pressure is in the range from 3000 Pa to 7000 Pa, the displacement of the origami structure within 20 seconds shows a significant positive curvature growth trend with the increase of the peristaltic pressure, from about 1 mm to about 15 mm.

Fig. 6(a) shows screenshots of the movement process of the origami structure under different intestinal peristaltic pressures. Therefore, intestinal peristalsis pressure has a significant impact

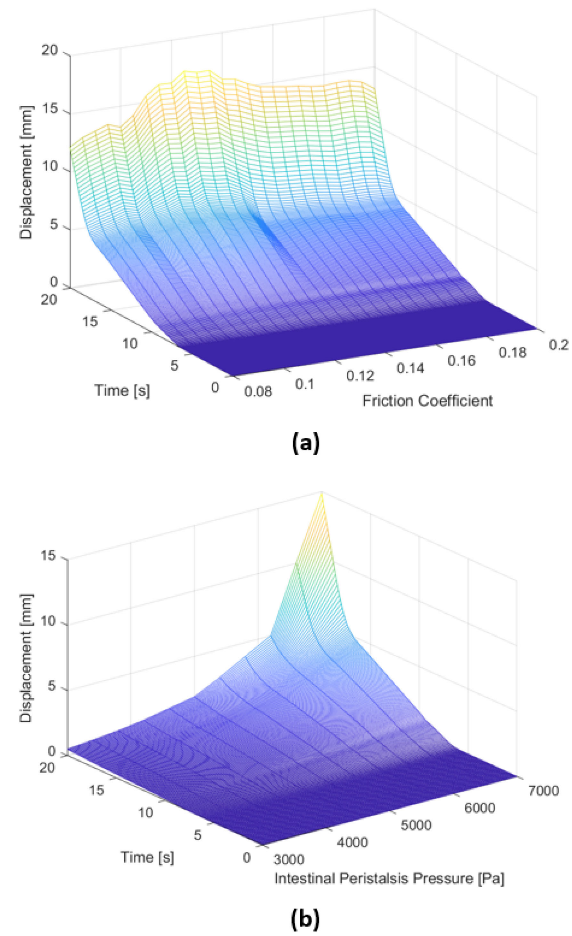

Fig. 4. Simulation results: relationships between **(a)** friction coefficient and the displacement **(b)** intestinal peristalsis pressure and displacement.

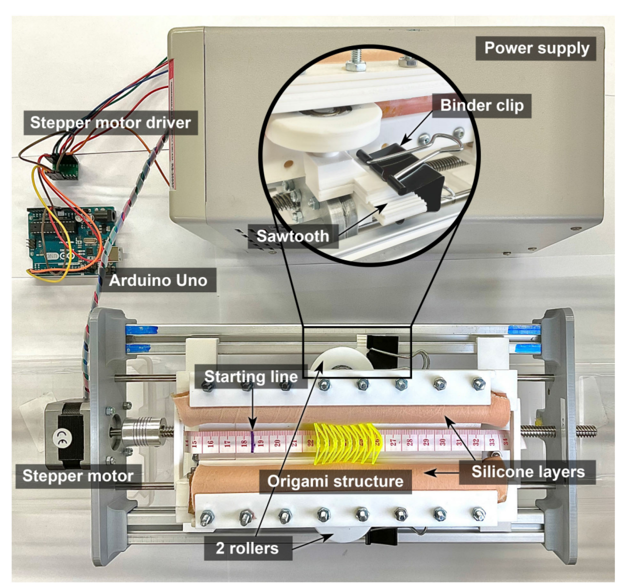

Fig. 5. Overall experiment set-up. The intestinal peristalsis waves were generated by a stepper motor which attached to a bolt screw and two 3D printed rollers mounted on the rail guide. The speed and the length of the peristalsis wave was controlled by an Arduino Uno microcontroller. To mimic the internal walls of the intestine, we used two silicone layers.

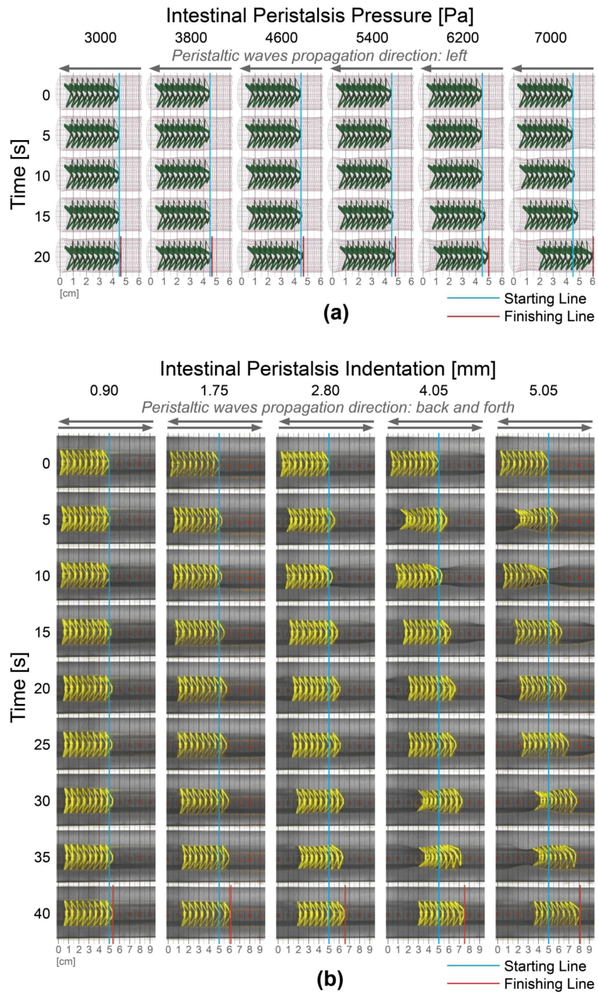

Fig. 6. Snapshots of simulations and experiments. **(a)** A series of snapshots taken during simulations. When the friction coefficient is 0.15, the motion state of the origami structure under different intestinal peristaltic pressures. Columns represent the intestinal peristalsis pressure and time stamps are shown in rows. The blue line is the starting position of the model's head, and the red line is the position where the head reaches at 20 seconds. **(b)** A series of snapshots taken during experiments (with lubrication). Columns represent the different intestinal peristalsis indentations and time stamps are shown in rows. The blue line is the starting position of the model's head, and the red line is the position where the head reaches at 40 seconds.

on the movement efficiency of the structure, and the greater the pressure, the faster the movement speed.

D. Fabrication

The proposed origami structural prototype was fabricated using 3D printing technology. A Original Prusa i3 MMU2S printer was used to fabricate the models. The printing accuracy was 0.15 mm and the material used was TPU (SAINSMART, shore hardness: 95 A).

III. Experiments and Results

We conducted a set of experiments to test the behaviour of the proposed origami structure in a simulated intestine. The goal of the experiment was to observe the motion of the proposed origami structure when we vary the peristaltic pressure and friction between intestine walls and the origami structure. The overall experiment set-up is depicted in Fig. 5. We used two silicone layers (Smooth-on Ecoflex 00-30) to realize the intestine walls. In order to produce the peristaltic waves, we designed a linear rail guide based system and two rollers mounted on the rail was used to indent outer side of the two silicone layers to simulate the wave. A ball screw attached to NEMA 17 stepper motor was used to produce the motion of the rail guide. Motion of the rail guide from left to right (as shown in the Fig. 5), produced the forward peristaltic wave. We restricted the wave displacement to 130 mm. The two rollers (diameter: 40 mm) were 3D printed with PLA and two bearing were fitted to help with the mounting. To vary the peristaltic pressure during the experiment, we simply changed the indentation distance of two rollers.

To measure the intestinal width of the experimental device, when the roller was not installed, we randomly selected 5 places on the intestine to measure the distance between the walls of the intestine using a vernier caliper, and calculated the average value as 24.40 mm, which was taken as the width D of the intestine. In order to measure the amount of peristaltic indentation used in the experiment. The two rollers are clamped in the same position on the sawtooth plane as shown in Fig. 5 by the clamp. The roller can slightly squeeze the intestinal wall to form a peristaltic wave. We randomly move the roller to 5 positions on the intestine, use a vernier caliper to record the distance between the crests of the peristaltic waves on both sides of the intestine, and obtain the average value as i_1. Then, move the two rollers inward by a zigzag distance, and repeat the above steps again to obtain i_2. Then repeat the above steps to measure i_3, i_4 and i_5. Finally, the peristaltic Indentation (peristaltic wave amplitude) a_1 to a_5 is obtained by the following formula:

$$a_n = \frac{(D - i_n)}{2} \tag{8}$$

In the experiment, we move the rollers to the right end of the intestine, place the tail of the origami structure at the starting point of the left end of the intestine marked by Fig. 5, and then turn on the power switch, let the rollers move back and forth along the intestine 5 times (this process takes 40 seconds in total), record The displacement of the tail of the origami structure under different conditions. Because the rollers move back and forth in the intestine, it is not all antegrade waves, but in preliminary experiments we found that retrograde waves hardly cause displacement of the origami structure. In addition to the antegrade wave, there are also retrograde waves in the real intestine [20]. The width of the origami structure is 24.40 mm, in order to be consistent with the experimental intestine width.

We conducted the following two sets of experiments. In experiment (Without lubrication), we used the origami structure to perform the above experiments under the peristaltic indentation of a_1 to a_5, and perform 10 experiments under each condition and calculate the average value. In experiment (With lubrication), before each experiment, an appropriate amount of soapy water was applied to the intestinal walls to simulate the lubrication of the mucus in the intestine, and the origami structure was used for peristaltic indentation from a_1 to a_5 The above experiments were carried out under the conditions of each indentation amount, and the experiments were carried out 10

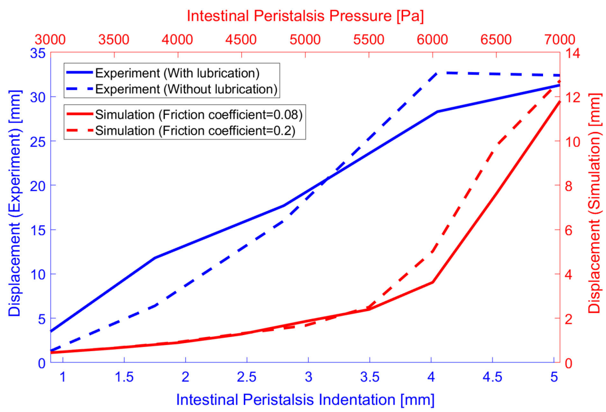

Fig. 7. Comparison of experimental and simulated results. Although the experimental and simulated conditions and units are different, we can still compare their trends. In both experiments and simulations, the greater the intestinal peristalsis intensity, the more significant the displacement of the origami structure, while the friction coefficient has less effect on the displacement.

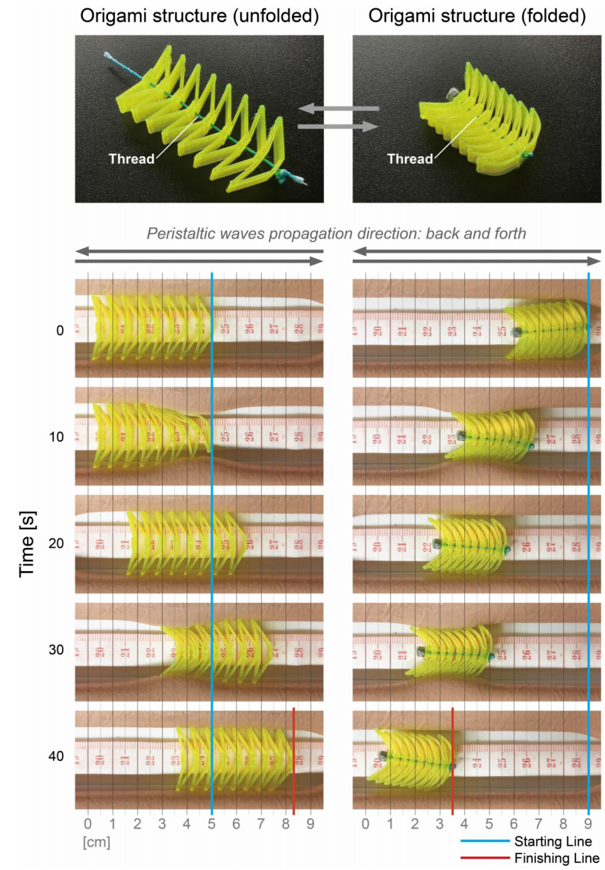

Fig. 8. Comparison of the motion of origami structures in unfolded and folded states. Columns represent the intestinal peristalsis pressure and time stamps are shown in rows. The blue line is the starting position of the origami structure's head, and the red line is the position where the head reaches at 40 seconds. After the origami structure is compressed by a thread that runs through it, it will be pushed in the opposite direction of motion by the origami structure when it is unfolded. Our next step is to use a micro-motor to pull this thread, which controls the capsule endoscope to change direction.

times under the conditions of each indentation and the average value was calculated.

A. Experimental Result

Fig. 7 shows the comparison of experimental and simulated results. We used two x-axes because we used different units for expressing the peristaltic strength of the intestine in our experiments and simulations. We used two y-axes because the experimental and simulated displacements are different. The lower x-axis is the amount of indentation of the intestinal peristalsis in experiments. The left y-axis is the displacement of the origami structure after being pushed back and forth 5 times by the peristaltic wave in experiments. The blue solid line represents the experimental results with the intestinal wall lubricated. The blue dashed line represents the experimental results without the intestinal wall being lubricated. The upper x-axis is the peristaltic pressure in simulations. The right y-axis is the displacement of the origami structure in simulations. The red solid line represents the simulation results with a friction coefficient of 0.08 between the origami structure and the intestine. The red dashed line represents the simulation results with a friction coefficient of 0.2 between the origami structure and the intestine.

It can be seen from Fig. 7 that the displacement of the origami structure in the experiment increases approximately linearly with the increase of the indentation of the intestinal peristalsis, and the results are not very different between lubricated and unlubricated conditions. The displacement of the origami structure in the simulation also continued to increase with the increase of the peristaltic pressure, starting from about 6000 Pa and becoming faster. Also in the case of low and high friction coefficients there is no very difference in the results. This indicates that the strength of intestinal peristalsis is a key factor in determining the moving efficiency of the origami structure, while the friction coefficient cannot significantly affect the moving speed.

Fig. 6(b) shows a series of snapshots taken during experiments with lubrication. The columns of the chart represent the different intestinal peristalsis indentations and time stamps are shown in rows. We can clearly see that when the intestinal indentation increases, the displacement of the origami structure increases.

In order to prove that the origami structure can change the movement direction of the capsule endoscope through the shape change, we did another experiment as shown in Fig. 8. We used a thread through the origami structure to compress it. We placed the compressed origami structure in the lubricated intestine under the peristaltic condition of 5.05 mm indentation moving back and forth, recorded its motion state within 40 seconds, and compared the motion state of the unfolded origami structure under the same experimental conditions. We found that the folded origami structure moves in the opposite direction to the unfolded origami structure as shown in Fig. 8. Although the direction of the peristaltic wave was back and forth in the experiment, the peristaltic wave from left to right hardly moved the folded origami structure, just as it could not move the unfolded origami structure. This is an interesting phenomenon, because we mentioned earlier that the peristalsis of the intestine sometimes has a retrograde phenomenon, and our origami structure can ensure that the movement direction of the capsule endoscope can be controlled in different peristalsis situation.

IV. Conclusion and Future Directions

In this letter, we proposed an origami structure for capsule endoscopes that can retrograde by intestinal peristalsis. It is composed of 9 crescent-shaped origami structures connected in series and 3D printed by soft TPU material. This structure can deform and move in the opposite direction to the direction of peristalsis during the process of being squeezed by intestinal peristalsis.

In the simulation, we found that the friction coefficient between the origami structure and the intestine had minor effect on the speed of the origami structure movement. However, we also noticed that intestinal peristalsis pressure has a greater effect on the speed. Within the range of 3000 Pa to 7000 Pa, the greater the peristaltic pressure, the faster the speed.

In the experiment, we noticed that the displacement of the origami structure increased approximately linearly with the indentation of intestinal motility. The results between lubricated and unlubricated conditions showed similar pattern, which also indicated that relative to friction, the strength of intestinal peristalsis was the key to the movement speed of the origami structure.

One of the main focuses of this letter was to demonstrate the relationship between the passive locomotion direction and the shape of the origami capsule. In future, shape control can be implemented using a worm-gear driven by a micro motor or an external magnetic field so that the motor does not have to experience a stall torque at rest. In addition, there have been reports of soft sticky food getting stuck in the throat of elderly people. Therefore, the soft capsule may pose such a risk. However, this risk can be minimized by having a safe method to contract it to a hard capsule before swallowing. Our next step is to make a capsule endoscope prototype that integrates a complete control system such as micro motor, battery, etc. to study its dynamics, control and power consumption.

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