In order to minimize the invasiveness of intestinal disease diagnosis and surgery, we propose an anchoring and extending micro-robot. The gait of the micro-robot was designed according to the biomechanical features of the intestinal tract. The locomotion condition showed that the anchoring capability and extending ability should be balanced to enhance locomotion efficiency. The mechanical and control system was designed and fabricated under the requirements of the locomotive model. The assembled micro-robot was 90 mm in length and 13 mm in diameter. The micro-robot prototype was tested in in vitro experiments; its locomotion efficiency was approximately 100% in an ideal environment, but around 50% in a pig's small bowel (20 mm in diameter). The in vitro experiment results demonstrated that the gait is feasible for locomotion in the small bowel although the diameter of the small bowel is a limiting factor.

**Keywords:** Micro-robot, Small bowel, Locomotion capsule

1. Introduction

Endoscopy plays an important role in the diagnosis and treatment of gastrointestinal (GI) tract disease. An endoscope is normally introduced manually via the patient's mouth or anus to acquire visual data of the internal surface of the GI tract. Endoscopy directly and effectively assists in the diagnosis of abnormalities, but it cannot be used in the lower GI tract.

A swallowable capsule endoscope (CE) is a non-invasive solution for full GI tract diagnosis. PillCam [1, 2] is a commercial wireless CE from Given Imaging (Israel). It consists of an image sensor, lighting source, radio frequency module and battery. Propelled by peristalsis, it passively travels in the alimentary canal; because it is not mechanically controlled, it cannot stop or reverse direction so suspected lesions cannot be examined repeatedly.

A controllable capsule micro-robot, on the other hand, is designed for active locomotion in the human GI tract. Because the micro-robot carries sensors and surgical tools, drugs may be delivered directly to the lesion spots, and living tissue may be sampled for preliminary biopsy by the micro-robot. With dedicated micro-scale mechanisms or magnetic field guidance, it can be controlled by surgeons. A multi-segment, worm-like micro-robot was proposed by L. Lin et al. [3] and was further developed by K. Wang et al. [4]. It is driven by friction between the inner intestinal tract wall and the robot shell, and is capable of climbing small slopes. An eight-legged capsule robot [5, 6] was designed and tested by M. Quirini. Its leg motion is driven by micro direct-current motors. A padding-based robot [7, 8] was introduced by S. Park and was tested by H. M. Kim. This robot can unfold and manoeuvre six paddles for self-propulsion. Similarly, Y. Zhang et al. [9] introduced a diameter-variable capsule robot driven by an external rotating magnetic field.

Although many efforts have been made to meet the requirements of intestinal tract locomotion, an ideal solution has not yet been obtained in in vivo trials. The biomechanical features mostly rely on the smooth muscles of the muscularis externa layer. Various experiments [10–14] have attempted to model the passive behaviour of the intestinal walls and friction between intestinal walls and contents. Due to the complexity of the responses under mechanical stimulation, no model has been able to perfectly demonstrate the mechanical interaction needed for travelling through the small bowel.

This paper proposes a micro-robot that can propel itself through the small bowel by anchoring and extending. The gait of the micro-robot is introduced according to the biomechanical features of the small bowel. The locomotion condition and efficiency of the proposed model is discussed. The mechanical and control system is designed and fabricated. An in vitro experiment is performed to verify the model.

2. Biomechanics and locomotion analysis

In this section, we discuss the biomechanical features of the GI tract and the design and analysis of the micro-robot's gait.
Because the small bowel is the longest portion of the GI tract and an endoscope cannot be introduced into it, analysis and design in this paper are based on a small bowel environment.

2.1. The features of the small bowel
In an adult male, the small bowel is about 5.5 m long and approximately 25 cm in diameter. Due to muscle tone in a living body, the small bowel can be about 30% shorter than at autopsy. It can be divided into three sections: the duodenum, the jejunum and the ileum. The duodenum is C-shaped with a length of about 25 cm, and it joins the stomach and small intestine. The duodenum and the jejunum play different roles in digestion but have almost the same biomechanical features. The small bowel is suspended by mesentery, so it is capable of great mobility in the abdomen.

In histology, the three aforementioned sections mainly consist of four layers: serosa, muscularis externa, submucosa and mucosa. The serosa comprises a thin layer of cells that cover the small bowel’s outer wall; its main function is to reduce friction from bowel movements. The muscularis externa has an inner circular and outer longitudinal layer of smooth muscles; it uses peristalsis to propel bolus. The submucosa joins the mucosa to the muscularis externa, and the mucosa directly contacts the bolus.

The main biomechanical feature of the small bowel is its viscoelasticity [14, 15], which consists of creep, relaxation, anisotropy and nonlinear stress–strain relation.

2.2. Gait
A model of an anchoring and extending micro-robot is illustrated in this section. The anchoring motion provides alternative friction for two segments of the robot, whereas the extending motion pushes or drags the two segments.

The micro-robot is equipped with one extending and two anchoring mechanisms. The anchoring mechanisms are located in the front and rear cabins. Using universal joints, the body of the extending mechanism is jointed with the rear cabin, and its moving end is jointed with the front cabin. When the anchoring mechanisms are both unfolded, the robot generates the maximum friction force against the intestinal wall so as to stay in relative rest (see figures 1(a) and 1(d)). To complete a forward extension, the robot folds its front cabin (figure 1(b)) and extends its middle cabin (figure 1(c)). Then by unfolding its front cabin (figure 1(d)), folding its rear cabin (figure 1(e)), and contracting its middle cabin (figure 1(f)), the robot completes a forward contraction. By following the above motion sequence, the robot takes a forward step, and, by reversing the above sequence, the robot travels backward.

2.3. Locomotion condition
The locomotion condition is analyzed in Figure 2. In the extending stage, the front cabin is pushed by the extending mechanism with thrust force $F_{\text{Push}}$. The friction force between the front cabin and intestinal wall is $f_{\text{Front}}$, and the resistance at the end of front cabin is $F_{\text{Resis}}$. The condition of the front cabin moving forward is

$$F_{\text{Push}} > f_{\text{Front}} + F_{\text{Resis}} \quad (1)$$

The rear cabin is pushed by the mutual force of $F_{\text{Push}}'$. The unfolded anchoring mechanism provides friction $f_{\text{Rear}}$, and the resistance at the end of the rear cabin is $F_{\text{Resis}}'$. The condition of the rear cabin staying in relative rest is

$$F_{\text{Push}} < f_{\text{Rear}} + F_{\text{Resis}}' \quad (2)$$

In the contraction stage, the front cabin drags the rear cabin by force $F_{\text{Drag}}$ and hold its position by the unfolded anchoring mechanism with friction $f_{\text{Front}}'$. The condition of the front cabin staying in relative rest is

$$F_{\text{Drag}} < f_{\text{Front}}' \quad (3)$$

The friction between the rear cabin and intestinal wall is $f_{\text{Rear}}'$, so the condition of the rear cabin moving forward is

$$F_{\text{Drag}} > f_{\text{Rear}}' \quad (4)$$

The requirements for mechanism design can be deduced from equations (1) to (4). The first requirement is that the push or drag force should be large enough to overcome the friction or resistance but should not be larger than the maximum anchoring force that is provided by the motionless cabin. The
second is that the difference in the amount of friction between the folding and unfolding of the anchoring mechanism should be large as possible

### 2.4. Locomotion efficiency

Considering the viscoelastic character of the small bowel and the potential slippage of the anchoring legs, the micro-robot's step length becomes relatively small. The locomotion efficiency can be presented as

\[ \eta = \eta_c \eta_a \]  

where \( \eta_c \) and \( \eta_a \) are the efficiencies in stages of contraction and anchoring, respectively. The efficiency of contraction is directly related to the stress–strain relationship of the small bowels. Although the small bowel is composed of anisotropic viscoelastic tissue, to simplify the analysis, the standard linear solid (SLS) model [15] is used under two assumptions: an external force load and unload cycle would be short enough (i.e. shorter than 20 s), and the size of the external force would be far smaller than what would cause permanent tissue damage. The SLS model consists of two parallel systems: one containing a spring and a dashpot in a series, and one containing only a spring. The system can be modelled as follows:

\[ F + \tau_e \frac{dF}{dt} = E_R \left( u + \tau_o \frac{du}{dt} \right) \tag{6} \]

where \( F \) is stress, \( u \) is strain, \( \tau_e \) is isostress relaxation time, \( \tau_o \) is isotrain relaxation time, and \( E_R \) is relaxation elastic modulus. Under the unit step function, its creeping function is

\[ u = \frac{1}{E_R} \left[ 1 - \left( 1 - \frac{\tau_e}{\tau_o} \right) \exp \left( -\frac{t}{\tau_o} \right) \right] \tag{7} \]

For the SLS model, to reduce strain on the small bowel in extension and contraction, high stepping velocity and low \( F_{\text{Push}} \) and \( F_{\text{Drag}} \) are required.

The interaction between the micro robot and the intestinal tract is described in Figure 3. When the robot is introduced into the small bowel, the initial length of the small bowel is \( L_0 \) while it is in zero-stress states. In the first extending stage, the front cabin moves a forward steps \( s \), and the small bowel moves forward \( u_1 \) due to its elasticity. The same phenomenon happens in the contraction stage. The small bowel moves along with the rear cabin with length \( u_1 \) at first to reset in the zero-strain states, and then contracts with the rear cabin for length \( u_2 \). The efficiency of contraction is

\[ \eta_c = \frac{s - u_1 - u_2}{s} \tag{8} \]

In the second extension stage, the micro-robot overcomes the history strain \( u_2 \) and then forces the small bowel to extend by length \( u_1 \). In the second contraction stage, the small bowel and micro-robot behave the same as in the first contraction stage, so the efficiency of the second contraction can be expressed as in equation (8).

Slippage can be avoided by the leg fastening securely to the small bowel. Due to safety concerns, the leg stretching force is controlled under a threshold, which prevents mechanical damage to the small bowel but may cause slippage of the legs. The maximum legged diameter of the robot is designed to mirror the diameter of the small bowel to decrease the chance of slippage.

### 3. Micro-robot prototype

The system prototype is shown in figure 4. It is a three-cabin structure. The front cabin has an anchoring mechanism and a video-capture module, the middle cabin an extending mechanism and an on-board control and communication circuit board, and the rear cabin another anchoring mechanism. This system is 13 mm in diameter and 90 mm in length when its actuation mechanisms are folded.

All three mechanisms are driven by brush direct current (DC) motors produced by Constar Micromotor, Guangdong, China. It is 6 mm in diameter and 10 mm in length with a rated speed of 11 300 rpm and a rated torque of 0.12 m Nm. According to the features of the motor, the gearbox should be designed to reduce the speed and to increase the torque.

The video-capture module is in the front of the micro-robot. It consists of a lens, CMOS sensor, lighting source, micro controller, and radio frequency (RF) transmitter circuit. The video is 29.9 frames per second and 320 × 240 pixels in resolution.
3.1. Mechanical design

The anchoring mechanism consists of six bars, separated into three groups and mounted on two nuts with two drive screws parallel to the motor. Each screw is designed with two separated threads with an opposite-hand spiral. The two thread segments have the same stroke and lead. Because the two drive screws are mounted on the output stage of the gearbox, the three groups of bars move simultaneously.

A two-bar, two-slider structure was designed. Each bar connects with a slider at one end, which connects with another bar at the other end. The bars are of equal length. When the sliders move along a line in the opposite direction, the bar hinges move perpendicular to the line. This structure transforms the displacement—which was parallel to the motor axis—to the perpendicular direction. In this mechanism, the slider is attached with a nut. To avoid extra bending force, the relative position of the bar joints and screw holes is carefully assigned.

To match the required speed and force, a reducer is designed with a micro-normal-module spur gear. The output stage of this gearbox has two gears, each of which mounts on a separate drive screw. These two gears are meshed with a same gear to ensure that the screws rotate synchronously.

The theoretical values and measured values of the relationship between radial displacement and stall force are shown in figure 5. Stall force increases rapidly after 3.5 mm of radial displacement, so it is mechanically limited due to safety concerns. The stall force in the radial displacement range of 0 mm to 3.5 mm is 0.85 N on average for each leg.

The extending mechanism consists of a drive screw and nut pair, which is driven by a speed reducer. The output stage of this gearbox has two gears, each of which mounts on a separate drive screw. These two gears are meshed with a same gear to ensure that the screws rotate synchronously.

The extending mechanism consists of a drive screw and nut pair, which is driven by a speed reducer. The output force is delivered by a moving plate that connects with the nut via bars, and the moving plate is guided by two micro-linear bearings on the rear plate.

To maximize the efficiency of the nut and screw pair, the position of the bars between nut and moving plate is noted. If one bar is used to connect the nut and moving plate, the efficiency will decrease because the external force does not act in the axial line of the screw. Compared to a one-bar solution, two bars located symmetrically by the axial line can avoid the bending moment. But the moving nut requires a certain amount of space, which in volume takes about 24% of the entire extending mechanism.

To help the screw rotate smoothly, two micro ball-bearings are used to mount the screw on both front and rear plates. A space of 0.6 cm³ is reserved to mount an on-board printed circuit board.

The test result for the relation between force and speed illustrates that the linear-moving nut is mechanically symmetrical (see figure 6). With rated motor speed, the pulling and pushing force is about 2.7 N.

3.2. On-board circuit

The on-board circuit board consists of a three-channel brush DC motor driver, a micro control unit (MCU) that acquires
the driver current via a current sensor, and radio frequency module that communicates with the external console. The fabricated main circuit board is 10 mm × 8 mm × 3 mm, and the power regulator board is 6 mm × 7.5 mm × 4 mm (see figure 7). It is designed to attach to the middle cabin, along with the extending mechanism.

3.3. Robot control system

The control system is divided into two parts: an on-board motion controller and an external console. The on-board motion controller consists of a motor current control, a single mechanism motion control and a gait control. The on-board controller receives and executes commands from the external console, which is based on a personal computer and programmed in Visual C++. The console (see Figure 8) accepts a human input command, then encodes the command and transmits the message through the local serial port, where an additional wireless data transmit device is plugged in.

The safe threshold of the on-board motor, and the allowable over-current timing can be configured though the external console. Both the single motion of each mechanism and the robot gait can be controlled as well.

The motors are driven by H-bridge, and the motor current is indirectly sampled; also, a current close-loop control can be performed. After the micro-robot first powers on, each motor is driven for about 500 ms with the current sampled to detect mechanical and electrical failure.

To control the robot’s forward and backward movement, the on-board micro controller works in a ‘gait pattern’. According to the gait (analysed in §2), there are six motion statuses and one idle status. So a state machine with seven statuses was designed to support this working pattern. Because the on-board circuit is powered by wireless power transmission, to keep the micro-robot moving smoothly, the current status of the gait is recorded in a micro controller on-chip EEPROM; and the status before it powers down is self-restored after the system is re-initialized.

4. In vitro experiment

To examine the functionality of the micro-robot, two types of experimental environments were constructed. A flexible tube was used to stimulate the human small bowel to verify the mechanical characteristics in an ideal environment. A pig small bowel was used to test the locomotion in a phantom model because the pig small bowel is similar to that of a human in biomechanics and morphology.

To simulate the layout of the small intestinal tract in the abdomen, a flexible tube was suspended by both ends on a
5. Discussion

Stimulated experiments show the micro-robot working properly. The efficiency of locomotion is close to 100% because no contraction step was lost and no leg anchoring slippage occurred. The experiment results demonstrate that the micro-robot is suitable for locomotion in an ideal small bowel tube.

An in vitro phantom experiment shows the robot is not suitable for a small bowel with a diameter larger than 20 mm. Because the maximum extension of each anchoring leg is 3.5 mm, when an anchoring mechanism unfolds, the small bowel is stretched into a triangle with sides of approximately 18.2 mm, which is equal to a circle of 17.3 mm in diameter. Each of the three legs in one anchoring mechanism makes contact with the small bowel when the diameter is under 18 mm. With a diameter between 18 mm and 22 mm, the efficiency of the anchoring mechanism decreases. When the diameter is larger than 22 mm, the anchoring mechanism loses effectiveness and equations (2) and (4) are not obeyed, so the micro-robot can no longer manoeuvre.

6. Conclusion

The design, fabrication and testing of this anchoring and extending micro-robot demonstrate a novel approach to non-invasive small bowel inspection and therapy. The experiments show that the prototype is suitable for locomotion in an ideal tubular environment but cannot adapt to one that is larger than 22 mm in diameter due to anchoring leg length.

To adapt to small bowels of various diameters, the length of micro-robot’s legs should be controllable. Further study will focus on the relationship between leg number, length, and force for safer and reliable anchoring. Also, a micro force sensor should be deployed to ensure small bowel safety by directly or indirectly sampling the leg tip’s contact force. Meanwhile, a wireless power supply system [16] should be equipped on the micro-robot for further in vivo study to enhance micro-robot locomotive flexibility.

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References