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Capsular Locomotive Microrobot for Gastrointestinal Tract

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***Abstract*— Diagnosis using a flexible endoscope in gastro-intestinal tract becomes very important. In addition, the endoscope is a basic tool of diagnosis and treatment for digestive organ. However, the operation of endoscope is very labor intensive work and gives patients some pains. Therefore, the capsule-type endoscope is developed for the diagnosis of digestive organs. For its conveniences for diagnosis, the capsule endoscope comes into the spotlight. However, it is passively moved by the peristaltic waves of gastro-intestinal tract and thus has some limitations for doctor to get the image of the organ and to diagnose more thoroughly. In order to solve these problems, therefore, a locomotive mechanism of capsule endoscopes has being developed. For the locomotion in the gastro-intestinal tract, our proposed capsule-type microrobot has synchronized multiple legs that are actuated by a linear actuator and two mobile cylinders inside of the capsule. For the feasibility test of the proposed locomotive mechanism, a series of in-vitro experiments using small intestine without incision were carried out. In addition, in-vivo animal tests under a general anesthesia are also executed. From the experimental results, we conclude that the proposed locomotive mechanism is not only applicable to micro capsule endoscopes but also effective to advance inside of intestinal tract.**

I. INTRODUCTION

THE conventional push-type flexible endoscope is most commonly used in most hospitals and operated by the hands of skilled individual operator. Since its tube needs some structural strength to be pushed, it has somewhat high stiffness, causing pain and discomfort to the patient. Moreover, it cannot reach to the small intestine for diagnosis. These problems caused the development of wireless capsule endoscopes. The first capsule endoscope called the M2A [1, 2, 3] was developed and commercialized by Given Imaging Inc. of Israel. It has a dimension of 10 mm in diameter and 27 mm long and consists of a CMOS camera, an RF module, illuminating LEDs, and a battery. It can be swallowed and can transmit wireless still images (2 frames/sec) from the gastro-intestinal tract. Due to the development of wireless capsule endoscopes, it is now possible to diagnose small intestines, which can not be achieved by conventional endoscopes, and to reduce pain and discomfort of the patient.

However, the capsule endoscopes move passively from the mouth to anus by the peristaltic waves of the digestive organ. Therefore, no active diagnosis is possible due to the lack of a locomotive capability. For doctor to get the image of the organ and to diagnose more thoroughly, a locomotive mechanism of capsule endoscopes is necessary. However, the gastrointestinal tract consists of soft and local deformable tissues and has very slippery surfaces with the secretion of mucous. Therefore, the intestinal tract is very tough environment for a locomotive mechanism.

For general locomotive robot, legged robots have been studied [4, 5, 6] but the proposed legged mechanisms are not applied to capsule locomotion and not easy to miniaturize. As an example, legged locomotion in gastro intestinal tract has been proposed [7]. The locomotive mechanism is based on active multiple legs which have independent degrees of freedom. Since it uses multiple legs, the locomotive mechanism needs multiple actuators and controllers. Therefore, the multi-legged locomotion mechanism can have the limitation of power consumption and miniaturization.

In addition, we had proposed an inchworm-like microrobot comprising actuation modules and clamping modules for capsule endoscopes [8, 9, 10]. In order to realize high stroke of locomotive mechanism, spring type SMA (Shape Memory Alloy) actuators have been employed but SMA actuator has very low efficiency and slow response time since it actuates SMA. In addition, more than two actuators are required to have long stroke and strong force enough to get over resistance force due to friction and visco-elastic deformation of small intestine [11, 12, 13, 14].

In order to solve the problems, we propose a new paddling based locomotive mechanism. The proposed locomotive mechanism is originated from paddling a canoe in Fig. 1. The paddle of a canoe is embodied as the legs of our microrobot and the canoeist is replaced by the linear actuator which is composed of a reliable commercialized micromotor and a lead screw.

The paper is organized as follows: In the following section, the locomotive mechanism of the proposed microrobot will be explained. Section III will introduce the fabrication of the proposed microrobot and the control system. Through the various in-vitro and in-vivo experiments in section IV and V, the feasibility of the microrobot was verified and the effects of the design parameters were illustrated. Finally, concluding remarks will be drawn in Section VI.

Fig. 1. Paddling a canoe

II. LOCOMOTION MECHANISM

First of all, the concept design of the microrobot is shown in Fig. 2. The proposed microrobot consists of a linear actuator which comprises micro motor and lead screw, an inner cylinder, an outer cylinder, multiple legs and robot outer body. The functions of the above elements are as follows:

- The linear actuator can move the inner cylinder backward and forward;
- The inner cylinder has grooves and there is some clearance between the grooves and the legs. Owing to the clearance, the inner cylinder makes the legs rotate and moves with the legs and the outer cylinder;
- The outer cylinder is connected with the multi-legs by wired-type pin and is moved inside of the robot outer body;
- The multi-legs are protruded from the robot outer body and are folded in the body. The robot has six legs which are radially positioned to contact with the intestinal tract; and
- Finally, in order to reduce the friction force between the robot outer body and the intestinal tract, the head of the robot is designed as a semi-sphere and the robot outer body is coated with lubricant such as silicon oil. And for the protruding and folding the legs, the robot outer body has the lateral slits.

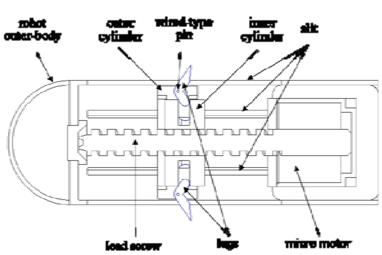

Fig. 2 Concept design of microrobot

The locomotive mechanism of the proposed microrobot is presented in Fig. 3. First of all, step (1) shows the initial state of the capsule-type microrobot, which is inserted into the intestine. In step (2), if the actuator moves the inner cylinder right, the legs are protruded and clamp the intestinal surface. In step (3), if the actuator moves the inner cylinder further, the legs do not protrude any more and the outer body of the microrobot advance to the left. And step (4) shows the end of the stroke of actuator. If the actuator moves the inner cylinder to the left in step (5), the legs which were fixed to the intestine are released and folded in the robot body. In step (6), the legs and the inner/outer cylinders moved to the left without the movement of the microrobot body. Finally, the robot becomes the same configuration of step (1). By this locomotion principle, our proposed capsule-type microrobot can be easily moved inside of the intestinal tract.

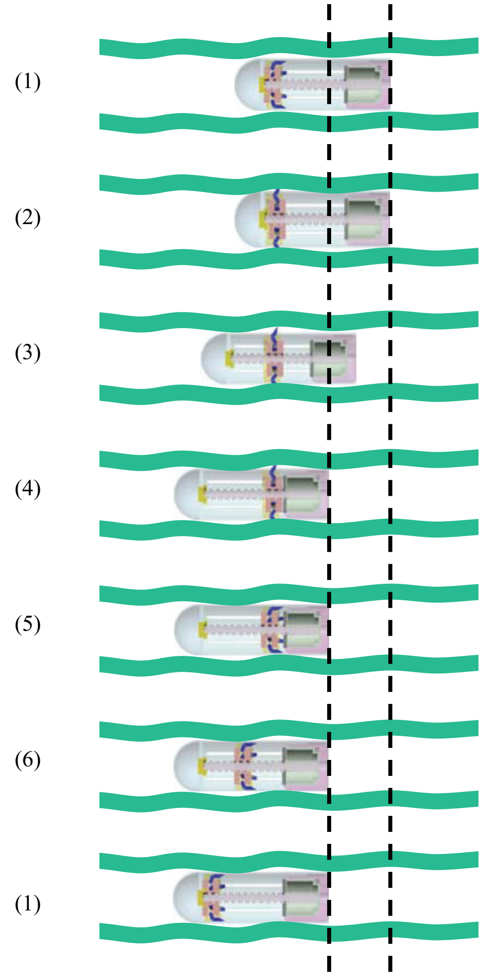

Fig. 3. Locomotion principle of the proposed capsule-type microrobot


Fig. 4. Fabricated legged microrobot

III. FABRICATION OF MICROROBOT AND CONTROL SYSTEM

The proposed locomotive mechanism is fabricated as shown in Fig. 4. The prototype uses the conventional micro step motor as an actuator and the lead screw for the linear motion. The outer body of the prototype microrobot was made as the capsule type and the outer diameter is set to about 13mm. The outer body of the microrobot, the inner cylinder and the outer cylinder were made of the polycarbonate. The legs are fabricated with SUS 304, manufactured by wire EDM (Electrical Discharge Machining). The total length of the capsule becomes 30 mm and the stroke of the legs that is decided by slits of the robot body. In this model, the stroke of linear actuator is adjusted to 15mm and the theoretical moving velocity of the microrobot is about 9.38 mm/sec which is decided by the pitch of lead screw and the motor controller. The mass of the prototype is minimized up to 5.2 grams considering integrations of other components. For the actuation and control of the microrobot, the control circuit has the functions of position / velocity controls and direction change of the legs.

IV. IN-VITRO EXPERIMENTS

A. *In-vitro Test I (Planar Curved Path)*

For the feasibility test, the in-vitro experiments using small intestine obtained from live pig are executed. As shown in Fig. 5, it is spread on Styrofoam that has a straight and a half circle path, the radius of about 25, 30, and 40mm, respectively. And then our microrobot is inserted into the small intestine and can advance along the straight and a half circle path.

(a) R=25mm (b) R=30mm (c) R=40mm
Fig. 5. In-vitro experimental results I (R=25, 30, 40mm)

In addition, the velocities of the microrobot are measured from the video images and the locomotive performances of the microrobot are summarized in Table I. The velocities on the straight lines are about 6.00 ~ 6.50 mm/sec and 64 ~ 69 % of theoretical velocity. However, the velocities on the half circles are about 3.02 ~ 6.42 mm/sec and it is 32 ~ 68 % efficiency compared to theoretical velocity. When the radius of the half circle is 40mm, the velocity on the straight line is similar to that on the half circle. However, the velocities on the half circle with the radius of 25 and 30mm are much slower than that on the straight line. This is why the resistant force between the microrobot and the small intestine is significantly increased as the radius of the half circle decreases.

B. *In-vitro Test II (3D Curved and Sloped Path)*

For another in-vitro test, the small intestine just extracted from live pig is bridged across the two posts and thus the small intestine has 3-dimensional curved and sloped paths in Fig. 6, the slope angle of about 34, 63, and 78 degree, respectively. And then microrobot is inserted into the end of the small intestine and can advance along the 3D intestinal tract.

TABLE I
LOCOMOTIVE PERFORMANCE OF MICROROBOT FOR A PLANAR CURVED PATH

Path	Velocity on straight linear path (mm/sec)	Efficiency compared to theoretical velocity	Velocity on half circular path (mm/sec)	Efficiency compared to theoretical velocity
R=25mm	6.26	69.3 %	3.02	32.2 %
R=30mm	6.42	68.4 %	4.28	45.6 %
R=40mm	6.00	64.0 %	6.42	68.4 %

(a) Slope = 34 degree (b) Slope = 63 degree (c) Slope = 78 degree
Fig. 6. In-vitro experiments results II (Slope = 34, 63, 78 degree)

From the video images, the velocities of the microrobot in 3D intestinal tract are measured and the locomotive performances are summarized in Table II. The velocities on the 3D curved and sloped paths are about 3.29 ~ 6.26 mm/sec and 35 ~ 67 % of theoretical velocity. In addition, we find that the velocity of the microrobot is decreased as the slope angle increases because of the resistant force and the gravitational effect in the 3D curved and sloped path.

V. IN-VIVO EXPERIMENTS

In-vivo animal tests of IMC research will be carried out at Yonsei medical center in Korea, where has laboratories and medical facilities for animal tests. All animal tests in the Yonsei medical center will be executed according to "Guide

TABLE II
LOCOMOTIVE PERFORMANCE OF MICROROBOT FOR 3D CURVED AND SLOPED PATH

Path (Slope angle)	Velocity on 3D curved and sloped path	Efficiency compared to theoretical velocity
34 degree	6.26 mm/sec	66.7 %
63 degree	3.57 mm/sec	38.1 %
78 degree	3.29 mm/sec	35.1 %

for the Care and Use of Laboratory Animals" which is supplied by NIH (National Institutes of Health) in USA.

In this in-vivo locomotion test, the capsular microrobot is inserted into anus using overtube which guides the microrobot to large intestine and has diameter about 15 mm. The motion of the capsular microrobot is monitored by C arm mobile X-ray system. Fig. 7 shows the still image of the X-ray movie of the moving capsular microrobot. Through this in-vivo test, the proposed capsular microrobot can move along the large intestinal tract. In detail, the microrobot can travel the sigmoid pass, ascending tract, and gamma loop of pig's colon. The movies of the locomotion in the large intestine will be displayed in the conference site. Therefore, we can know that the proposed microrobot has feasible locomotive performances for the intestinal tract.

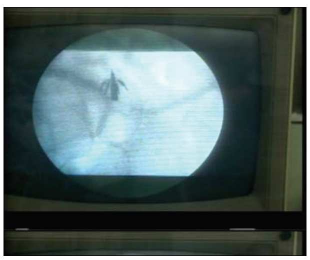

Fig. 7. Still image of the X-ray movie of the moving capsular microrobot in large intestinal tract

VI. Conclusion

In this paper, we developed a paddling based locomotive microrobot for capsule endoscope which has multiple legs and linear actuator. The multiple legs are sequentially unfolded and folded by inner and outer cylinder, and the inner cylinder is actuated by micro motor and lead screw. Since the proposed mechanism is actuated by the multiple legs and commercial micro motor, it has more reliable and repeatable performances and is less sensitive of the visco-elastic characteristics of the intestine. For the feasibility test of the proposed microrobot, the in-vitro tests using small intestine without incision were executed. In the locomotion test on a planar curved path, the microrobot could advance forward with the velocity of about 6.00~6.50 mm/sec on straight line path and about 3.02~6.42 mm/sec on curved path, which are 64~69 % and 32~68 % efficiencies compared to the theoretical velocity, respectively. From the result, the proposed microrobot on the curved half-circular path is slower than on the straight linear path owing to the restriction force between the microrobot and the small intestine. From another in-vitro test, we could know that our proposed microrobot can advance along the 3D curved and sloped path with the velocity of about 3.29 ~ 6.26 mm/sec and 35.1 ~ 66.7 % of theoretical velocity. In addition, as the slope angle increases, the velocity of the microrobot is decreased owing to the resistant force and gravitational effect in the path. In addition, in-vivo test in large intestinal tract is also executed and the capsular microrobot can move through the pig colon. Consequently, the proposed capsule-type microrobot shows good locomotive performances inside the small intestine tract and can be a good solution in order to relieve the problems of the previous capsule endoscope.

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