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Paddling based Microrobot for Capsule Endoscopes

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Abstract— **Recently, the capsule endoscope can be widely used for the diagnosis of digestive organs. 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. As a solution of these problems, therefore, a locomotive mechanism of capsule endoscopes has being developed. Our proposed capsule-type microrobot has synchronized multiple legs that are actuated by a linear actuator and two mobile cylinders inside of the capsule. By the novel kinematic relation between the legs and the mobile cylinders, the microrobot can easily move forward in the gastro-intestine. For the feasibility test of the proposed locomotive mechanism, a series of experiments were carried out including in-vitro and in-vivo tests. Based on the experimental results, we conclude that the proposed locomotive mechanism is not only easy to be used for micro capsule endoscopes but also effective to move inside of intestinal tract.**

I. Introduction

THE conventional push-type 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 in 2001 by Given Imaging Inc. of Israel. It is 10 mm in diameter and 27 mm long with a CMOS camera, an RF module, illuminating LEDs, and a battery integrated. It can be swallowed and can transmit wireless still and moving images 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. Another wireless type endoscope called Norika V3 is being developed by RF System Co. in Japan [4].

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 mechanism. In order to solve this problem, a locomotive mechanism of capsule endoscopes is necessary. For general locomotive robot, many legged robots have been studied [5, 6, 7] but the proposed legged mechanisms are not applied to capsule locomotion. As an example, legged locomotion in gastro intestinal tract has been proposed [8]. 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 thus can have the limitation of power consumption and miniaturization.

In addition, semi-autonomous robotic colonoscopies were proposed [9, 10, 11]. They are operated by pneumatic power and have steering, navigation, and diagnostic ability. However, they also have some problem on miniaturization as a capsule-size. Therefore, we had proposed an inchworm-like microrobot comprising actuation modules and clamping modules for capsule endoscopes [12, 13, 14]. In order to realize high stroke of locomotive mechanism, spring type SMA actuators instead of wire type SMA actuators have been employed. However, SMA actuator has very low efficiency and slow response time that is more than a few seconds since it actuates with heating SMA itself. 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 [15, 16, 17, 18].

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 proposed mechanism is hardly influenced by the folding of the intestine and less sensitive of the visco-elastic characteristics. In addition, because the microrobot uses a conventional micromotor, the locomotive mechanism has more reliable and repeatable performances.

Fig. 1 Paddling a canoe

The paper is organized as follows: In the following chapter, the locomotive mechanism of the proposed microrobot will

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be explained. Chapter III will present the design of leg mechanism and Chapter IV will introduce the fabrication of the proposed microrobot and the control system. Through the various in-vitro and in-vivo experiments in Chapter V and VI, the feasibility of the microrobot was verified and the effects of the design parameters were illustrated. Finally, concluding remarks will be drawn in Chapter VII.

II. LOCOMOTION MECHANISM

First of all, the locomotive mechanism of the proposed microrobot is described. The concept design of the microrobot is shown in Fig.2. The proposed microrobot consists of a linear actuator, which can be composed of 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.

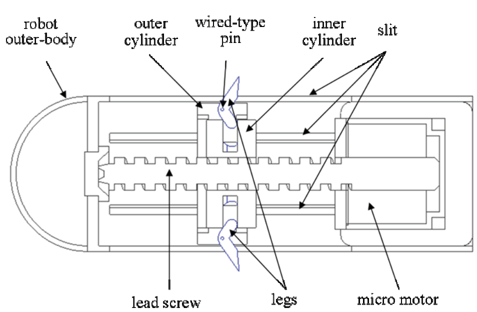

Fig. 2 Concept design of microrobot

The locomotion principle of our proposed capsule-type microrobot is presented in Fig. 3. First of all, step (a) shows the initial state of the capsule-type microrobot, which is inserted into the intestine. In step (b), if the actuator moves the inner cylinder right, the legs rotate on the axis of wired-type pin and clamp the intestinal surface since they are protruded. In step (c), if the actuator moves the inner cylinder further, the legs do not rotate any more and the outer body of the microrobot is advanced left. And step (d) shows the end of the stroke of actuator. If the actuator moves the inner cylinder left in step (e), the legs which were fixed to the intestine are released and folded in the robot body. In step (f), the legs and the inner/outer cylinders are moved left without the movement of the microrobot body. Finally, the robot of step (g) becomes the same configuration of step (a). By this locomotion principle, our proposed capsule-type microrobot can be easily moved inside of the intestinal tract.

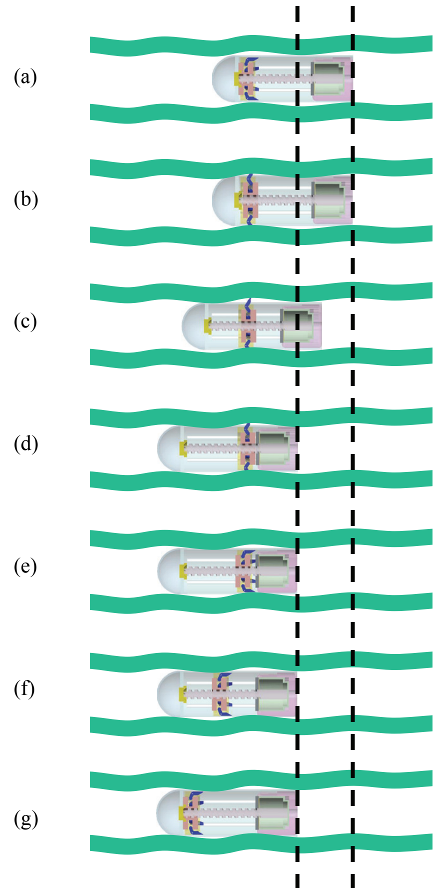

Fig. 3 Locomotion principle of the proposed capsule-type microrobot

III. LEG MECHANISM DESIGN OF CAPSULE-TYPE LEGGED MICROROBOT

The protruding and folding the legs are mainly dependent on the kinematic relation of the inner cylinder and the leg. The detail mechanism can be simplified and explained in Fig. 4.

In Fig. 4, (a) shows initial state; (b) is a neutral position between the inner cylinder and the leg; and (c) shows that the leg is fully protruded. In order for the leg to be folded into the robot body, as shown in Fig. 3, the angle of the leg should be designed as (90+ θ), where θ is decided by the kinematics of the inner cylinder and the leg. Finally, from the Fig. 4 (c), the protruded depth of a leg (h) is derived as

$$h = L_2 \sin(2\theta) \quad (1)$$

where L_2 is the lower length of the leg.

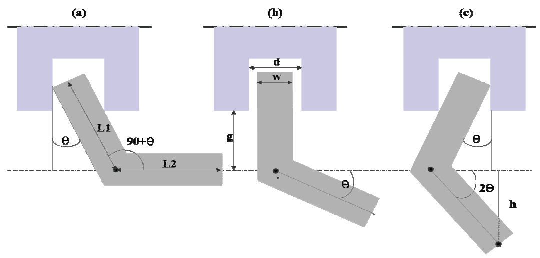

Fig. 4 Relation of the rotation of the legs.

As the above-mentioned, the protruded depth (h) is decided by θ and L_2, where L_2 is one of design parameters of the leg. However the value of θ can be derived from the kinematics of the inner cylinder and the leg. First of all, in Fig. 4, the parameters are defined as follows: d is the groove width of the inner cylinder, w is the width of the leg, L_1 is the upper length of the leg, and g is the distance between the inner cylinder and the rotational axis of the leg.

From the kinematic relation, the groove width (d) of the inner cylinder in Fig. 4 can be expressed as

$$d = w/2\left(\cos(\theta)+1/\cos(\theta)\right)+\left(L_1-g/\cos(\theta)\right)\sin(\theta) \quad (2)$$

where d , w , L_1, and g are all the design parameters of the legs. If the design parameters of the legs are given, therefore, the value of θ in Eq. (2) can be calculated by nonlinear equation solving tool (fsolve.m function) in MATLAB and thus the protruded depth (h) can be calculated from Eq. (1).

Fig. 5 The fabricated legged microrobot.

IV. Fabrication and Control Systems

The proposed locomotive mechanism is fabricated in Fig. 6. The prototype uses the conventional micro step motor as an actuator and the lead screw for the linear motion. The specification of the micromotor and the lead screw is described in Table I. 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. The wire that is used in order to fix the leg to the outer cylinder is stainless steel wire of 200 μm diameters. The total length of the capsule becomes 30 mm and the stroke of the legs that is decided by slits of the robot body and the stroke of linear actuator is about 15mm. The mass of the prototype is minimized up to 5.2 grams considering integrations of other components.

The control system is described in Fig. 6. In order to control the micromotor of the proposed microrobot, we constructed a motion controller which needs a power supply. By using the motion controller, the stroke and the torque of the micromotor can be adjusted. In order to measure the displacement of the microrobot, laser vibrometer is used, which is manufactured by Polytec with capability to measure range of 81.92 mm with 20 μm of resolution. For recording displacement data to PC, data acquisition board of dSPACE is used.

TABLE I
Specification of Micromotor and Lead Screw.

Motor Driving Voltage		5 V
Motor Diameter		10 mm
Motor Length		10 mm
Motor Torque	Holding	13.5 gf.cm
	Pull in (800 pulses/sec)	4.6 gf.cm
	Pull out (1400 pulse/sec)	6.0 gf.cm
Lead Screw	Pitch	1.876 mm
	Complete Thread	19.15 mm

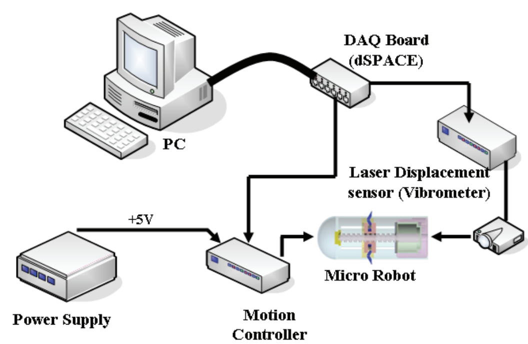

Fig. 6 System configuration to control the proposed microrobot.

V. Preliminary Experiments

The proposed microrobot is tested under various environments for feasibility test. For quantitative evaluation, the experiments on a paper surface are executed. And the experiments which uses dissected small intestine of dead porcine are also executed and the results are compared with those on paper surface.

Especially, in order to optimize the proposed microrobot, we executed many experiments under the variations of kinematic and dynamic design parameters. As kinematic parameters, the length and the thickness of the leg are chosen and as dynamic parameters, the stroke and the torque of the micromotor are selected.

Finally, the in-vitro tests using small intestine without incision that is extracted from live pig are executed. The small intestine without incision is very similar to the real in-vivo status and thus the locomotion test in this environment has important meaning for the feasibility of our microrobot.

A. Kinematic Design Parameter Variations

As kinematic parameters of the robot, the length (L_2) and the thickness (t) of the leg are selected. Since the leg shape is very important in the interaction the robot and the environmental surface. Especially, the length (L_2) of the legs is directly proportional to the protruded depth (h) in Eq. (1). That is, as the length (L_2) of legs increases, the protruded depth (h) is also increased. In addition, the thickness (t) of the leg is related with the contact surface area with the small intestine. Therefore, the deformed depth of small intestine depends on the length and the thickness of the leg. For the proper comparison, we selected the nominal value of the parameters and executed experiments under variation of one parameter, where the other parameters are used as the nominal values. The selected nominal values are set to the length (L_2=4.5mm) and the thickness (t=0.8mm).

Under the variation of kinematical parameter variations, the experimental results are shown in Fig. 7. Fig. 7 (a) and (b) are the results according to change of length (L_2=3.0, 4.5, 5.0 mm) and Fig 7 (c) and (d) are those according to change of thickness (t=0.5, 0.8, 2.0 mm). As the lengths of legs are changed as the abovementioned values, the protruded depths based on Eq. (1) are also changed as h=2.1, 3.1, and 3.5 mm, respectively. In these experiments, Fig. 7 (a), (c) and Fig. 7 (b), (d) present displacement on paper and on small intestine, respectively.

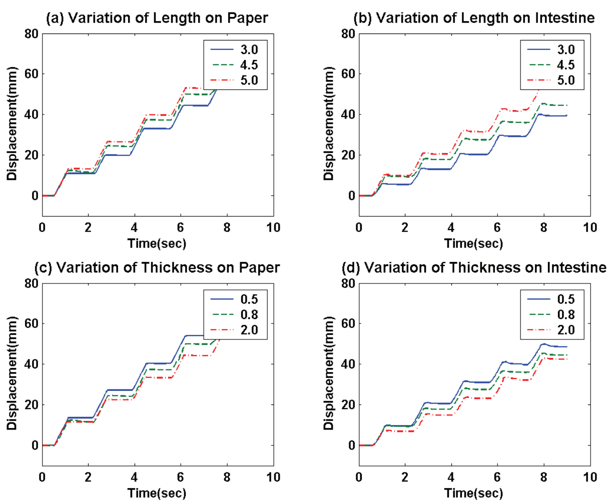

Fig. 7 Experimental results under variations of kinematic parameters.

From the experimental results under the variations of the kinematical parameters, we can conclude as follows:

- As the length of the leg increases and the thickness of the leg decreases, the displacement of the robot increases. From these results, we can find that the length and the thickness of the legs highly influence on the contact condition between the legs and the intestine. That is, if the length of the legs is longer and the thickness is thinner, the small intestine is more deformed and clamped with the legs, the slip between the legs and the intestine surface is also reduced and thus the displacement of the microrobot can be increased.
- The displacement of the microrobot on the paper is larger than that on small intestinal surface. It is expected that these results are caused by the visco-elastic property of the small intestine. That is, the viscous friction of small intestine is very larger than that of paper and the slip between the legs and the intestine surface is also increased by the relaxation characteristics of small intestine. Therefore, the advance of the microrobot per cycle is reduced.
- From the test results on the small intestine of Fig. 7 (b) and (d), we can observe a little retreat of the microrobot after an advance step. It is caused by the elastic characteristic of the small intestinal material. That is, after the microrobot advances a step, there is an elastic preload between the small intestine and the microrobot by viscous friction. If the legs are folded and the clamping force which supports the preload disappears, the elastic preload makes the microrobot go back a little.

B. Dynamic Design Parameter Variations

As dynamic parameters of the microrobot, we chose the stroke (s) and the torque (τ) of the micromotor, where these parameters can be easily changed in the motor controller. The stroke of the micromotor is somewhat different from stroke of legs. The difference is caused by the width of the inner cylinder and the clearance between the groove of the inner cylinder and the leg. Therefore, the stroke of the micromotor can directly affect the displacement of the microrobot. In addition, the torque of the micromotor is also related to the thrusting force of the microrobot and if the torque of motor is too small, the microrobot cannot overcome the friction between the microrobot and the environment surface.

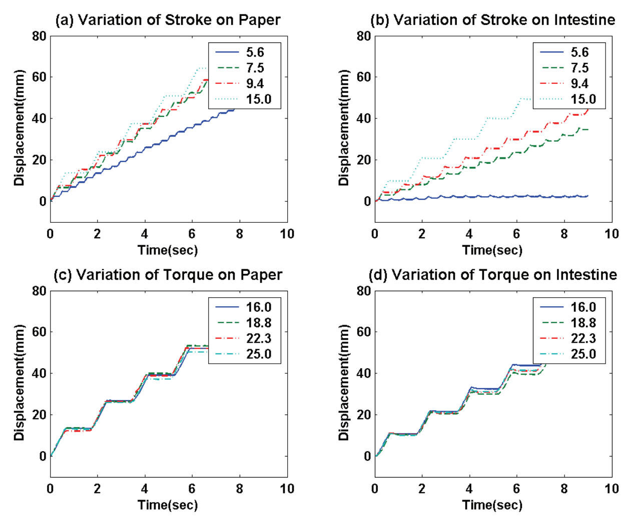

Fig. 8 Experimental results under variations of dynamic parameters.

As similar to kinematical parameter variations, we executed various experiments in case one parameter is changed and the other parameters are fixed. For the dynamic parameter variations, the experimental results are shown in Fig. 8. Fig. 8 (a) and (b) are the results under the various strokes (5.6, 7.5, 9.4, 15 mm); and Fig 8 (c) and (d) are those under the various torques (16.0, 18.8, 22.3, 25.0 gf.cm). Similar to the above results of Fig. 7, Fig. 8 (a), (c) and Fig. 8

(b), (d) present the displacement on paper environment and on small intestinal surface, respectively.

From the experimental results about the variations of the dynamic parameters, we can conclude as follows:

- As the stroke of the microrobot increases, the displacement of the robot increases. Especially, for the test on the intestine surface in Fig. 8 (b), the stroke of the microrobot becomes very important parameter. If the stroke of the microrobot is less than 5.6 mm, the microrobot on small intestine cannot advance forward. In Fig. 8 (b), if the stroke of the micromotor is 5.6 mm, the microrobot slightly moves forward in advance step. After the advance step, however, the microrobot goes back the same displacement. That is, the small intestine is deformed as much as the robot advances since the intestine has the viscous friction and the visco-elastic characteristics.
- The effect of the torque of the microrobot is nearly negligible. Therefore, we can know that the torque of the microrobot is sufficient enough to move on the paper and on intestinal surface.
- Similar to the results of the kinematic parameter variations, the displacement of the microrobot on the paper is larger than that on small intestinal surface. Compared with the paper surface, the small intestinal surface has visco-elasticity and large viscous friction, and thus the advance of the robot per cycle is reduced.

VI. In-vitro & In-vivo Experiments

For the following in-vitro and in-vivo experiments, the kinematic parameters of the microrobot are selected as the length (L_2=4.5mm) and the thickness (t=0.8mm) and the dynamic parameters of the microrobot are selected as the stroke (15.0mm) and the torque (25.0 gf.cm).

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.

(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.

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 %

C. In-vivo Test

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 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 large intestinal tract.

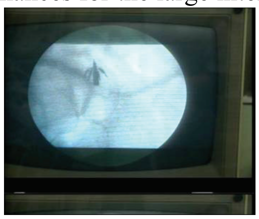

Fig. 7. Still image of the X-ray movie of the moving capsular microrobot in large intestinal tract

VII. 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. The proposed microrobot was tested on various environments such as on paper surface and on dead porcine intestine. The experiments of the variations of kinematic and dynamic parameters were executed and the effects of the parameters were examined. From the experiments, in order to improve the locomotion of the proposed microrobot for gastro-intestinal tract, the legs should have longer length and thinner thickness, which can reduced the slip between the legs and the small intestine. In addition, the stroke of the micromotor should be increased. 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.

Acknowledgment

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