KSTLE International Journal, Vol. 7, No. 2, December 2006, pp. 51-55

Frictional Behavior of Solid and Hollow Cylinders in Contact Against a Porcine Intestine Specimen

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Abstract: In order to design an effective foot surface which can provide adequate friction for a self-propelled medical microrobot moving inside the small intestine, frictional mechanisms between the small intestine inner wall and the foot surface of the robot must be understood. In this paper, mechanical interlocking effect was considered to design the surface of the foot that can generate the desired frictional force. The concept of the design was derived from the hookworm that lives inside the small intestine. Hookwarms are known to adhere to the small intestine wall by interlocking with villi on the surface of the small intestine. The interlocking mechanism was considered as the main frictional mechanism for the design of the microrobot foot surface in this work. 2 mm and 6 mm diameter solid and hollow cylindrical shaped foot specimens were designed and tested to assess the frictional force between the specimens and the porcine small intestine specimen.

Keywords: Endoscope, frictional force, intestine, mechanical interlocking, microsystem

1. Introduction

Effective ways for medical investigation or treatment have been developed and introduced to reduce the discomfort and improve the reliability of medical examination. Particularly, medical microsystems have been designed for minimal or noninvasive treatment without any incision of tissue in order to minimize the pain of patients and improve the convenience of examination. There is great motivation to develop such systems because they also have advantages to observe the affected parts directly inside the body and to inject medicine when needed.

At present, the capsule endoscope, which resembles a tablet has been developed and commercialized in Israel and Japan to examine gastrointestinal disease [1-2]. Technology for developing the capsule endoscope has already been achieved in Korea and efforts are underway to develop a self-propelling type of micro-robotic endoscope [3]. The capsule endoscope just needs to be swallowed by the patient and it goes through the gastrointestinal organs by natural peristaltic motion of the organs. Observation of inner part of the organs is done by various optical cameras and the images are transmitted and saved on a recorder outside of the body. However, the observation must be done while the capsule is moving inside body in real time, and therefore, the part that has been observed cannot be observed again by going back to that location. Moreover, the images are acquired at a rate of around two frames per second so it is difficult to observe a designated part for a long time in detail. Total examination time is also very long, being around 8 hours, and this can be inconvenient to the patient.

To develop an advanced high performance micro-robotic endoscope, real time observation, treatment, high speed and position control are needed. In order to propel the capsule endoscope inside organs, it is essential to generate relative motion between the inner wall of the organ and the micro-robotic endoscope foot. The propelling force must be large enough so that the endoscope can move through various resistive elements of the inner structures. Furthermore, it is necessary to design an effective surface which can generate sufficient frictional force against the organ surface.

In this paper, the interlocking mechanism of a hookworm, which is a parasitic inside the small intestine, was considered as the main mechanism for frictional force generation. Interlocking is the main mechanism of sticking its body on the small intestine wall so the interlocking mechanism can be used to generate the frictional force on the small intestine wall. The approach in this work was to use solid and hollow cylindrical structures to generate the interlocking effect between the foot of a capsule micro-robotic endoscope and the intestine wall. Experiments were performed to assess the frictional force between 2 mm and 6 mm solid and hollow cylindrical specimens and the porcine small intestine specimen.

2. Modeling and Experiment

2.1. Modeling of the interlocking mechanism of hookworm

Although it depends on the species of the hookworm, the hookworm (ancylostoma duodenate) has around 1 mm diameter and 10 mm length cylindrical shaped body and it has a

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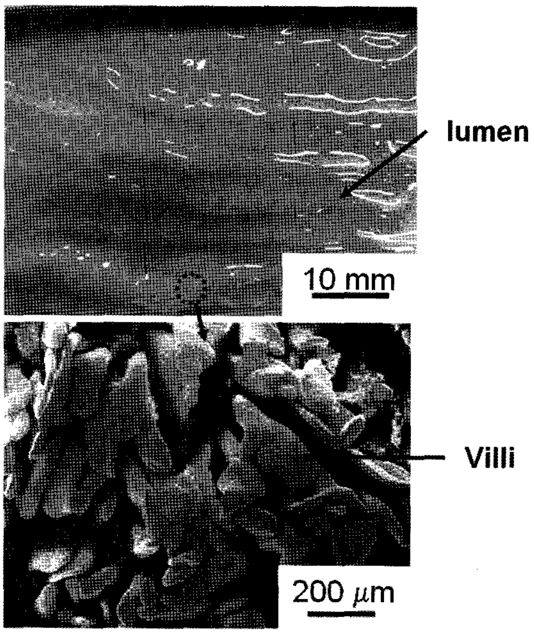


Fig. 1. Photograph of inner wall (upper) and SEM image of villi on the inner wall surface (lower) of small intestine of a pig.

relatively big mouth that is around 500 mm. Also, the mouth has four to six trigonal teeth that are around 150~250 μm in height. The hookworm uses the teeth to attach its body on the intestine surface and sucks blood. The teeth interlock with intestine surface structures such as villi or other micro scale surface structures [4].

Fig. 1 shows the photograph of inner wall and Scanning Electron Microscope (SEM) image of villi on the inner wall surface of small intestine of pig. In the photograph, there are lumen structures which are protruded parts in lines on the intestine surface and they are parallel with the longitudinal direction of the intestine. The villi shown in the SEM image can absorb nutrition from food inside the intestine.

When the size and shape of the teeth of the hookwarm are compared with those of villi on the small intestine surface, it can be readily noted that the teeth are very similar with villi in size and shape as shown in the SEM image in Fig. 1. Generally, before taking the SEM image, the specimen should be fixed by chemicals and the volume of the specimen usually shrinks around 10% after fixation [5]. Although the volume is decreased the amount of shrinkage is not critical and the size of villi is within the average tooth size of the hookworm. Because of the similarity in shape and size between the hookworm teeth and villi on the small intestine, it can be predicted that the hookworm teeth can effectively interlock with villi and penetrate the intestine surface to suck blood from the intestine.

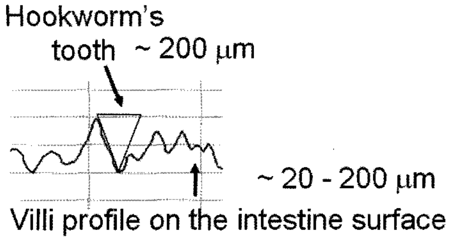
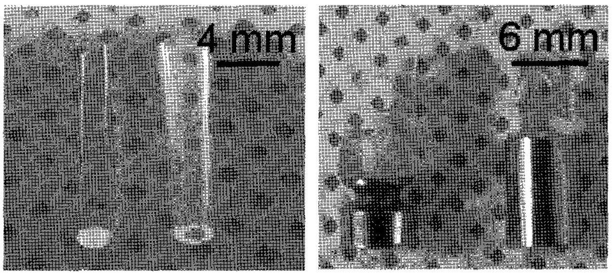


Fig. 2. Schematic of similarity in size and conformation between hookworm teeth and the villi of small intestine.



(a) (b)

Fig. 3. Photographs of (a) 2 mm diameter acryl solid cylinder (left) and hollow cylinder (right, 1.2 mm inner diameter), and (b) 6 mm diameter steel solid cylinder (left) and hollow cylinder (right, 5.4 mm inner diameter) specimens.

In this study, the interlocking mechanism between the hookworm teeth and villi was modeled as two principal factors. The two factors are penetration and interlocking due to similarity of the shapes and size between the two surfaces in contact. Fig. 2 shows the schematic of the interlocking state between the hookworm teeth and villi. The profile of the villi on the intestine surface was measured by using Laser Scanning Microscope (LSM) and it matched well with the shape and size of the hookworm teeth.

2.2. Experimental Details

In this study, the small intestine of a pig was used as the organ specimen because the porcine small intestine has similar size and structure with the small intestine of a human. The porcine small intestine was taken freshly after being butchered and the intestine was transported to the laboratory by putting the intestine into a package with saline solution to keep it at a pH value of about 7. The experiments were done within 5 hours of being butchered. Physiological and mechanical change of the biological specimen can be delayed by keeping the pH value of its original environment. Therefore, the change of the shape and size of the microscopic structures such as villi was minimized.

In order to investigate the effects of penetration and interlocking mechanism, two types of solid and hollow cylindrical shaped specimens were fabricated as shown in Fig. 3. The 2 mm diameter specimens(a) were made of acryl and the 6 mm diameter specimens(b) were made of steel because of convenience of fabrication.

In a previous study, it was shown that the material type was not a critical factor in dictating the frictional force between a solid surface and the porcine small intestine [6]. Therefore, the fact that two different materials were used in the experiments is not expected to effect the frictional force of the cylinders significantly.

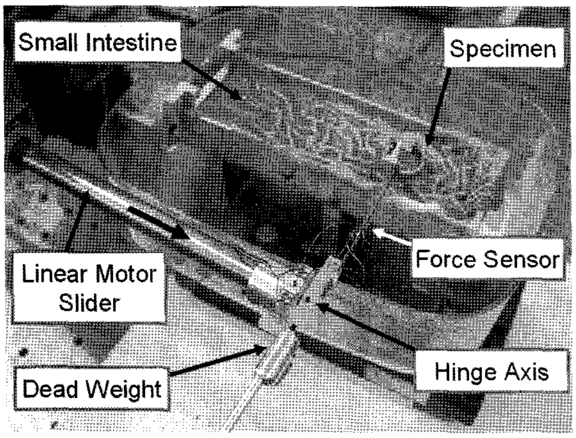


Fig. 4. Experimental set-up for frictional force measurement between specimen and the small intestine.

Frictional tests were performed using these specimens to analyze the effects of interlocking and penetration effects while the specimens were slid against the small intestine surface. The cylindrical specimens were placed vertically on the intestine specimen under a given load and it made a circular contact area with the intestine. Then the cylindrical specimen was moved at a specified speed. The frictional force was measured by the experimental set-up shown in Fig. 4. As shown, the linear motor slider moves to the direction of the arrow in Fig. 4. When the specimen attached at the tip of the force sensor slides on the intestine surface, the frictional force between the specimen and the small intestine surface is measured by the force sensor. The force sensor body is connected to the tip of the linear motor slider by a ball bearing hinge with very low friction so that the sensor body can freely rotate about the hinge axis. By moving the dead weight close to or far from the hinge axis, it was possible to apply a desired normal load between the specimen and the small intestine surface.

3. Results and Discussions

3.1. Frictional behavior of 2 mm and 6 mm cylinder specimens

Fig. 5 shows the experimental results performed using the set-up in Fig. 4 with the 2 mm solid and hollow cylinder specimens. Fig. 5(a) shows frictional force while the solid cylinder slides on the small intestine and Fig. 5(b) shows frictional force of the hollow cylinder. The same normal load (2 gf), sliding speed (10 mm/s), and sliding distance (100 mm) were applied in both cases. It can be seen in Fig. 5(a) and Fig. 5(b) that the average frictional force over the sliding distance of the solid cylinder is 1.5 gf, which is a little higher than 1.2 gf of the hollow cylinder. In particular, Fig. 5(a) shows a higher first stage friction of about 2.5 gf at around 15 mm distance. Thus, the solid cylinder shows a little higher average frictional force.

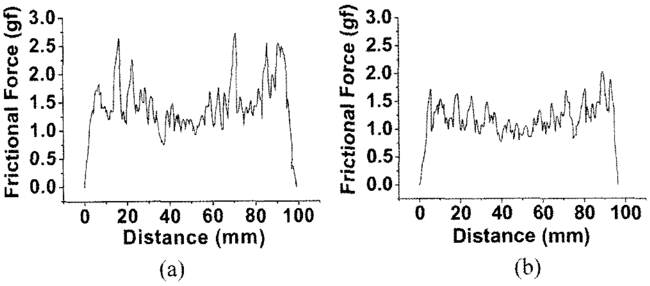


Fig. 5. Frictional force between small intestine and 2 mm diameter (a) solid cylinder, and (b) hollow cylinder at 2 gf normal load and 10 mm/s sliding speed.

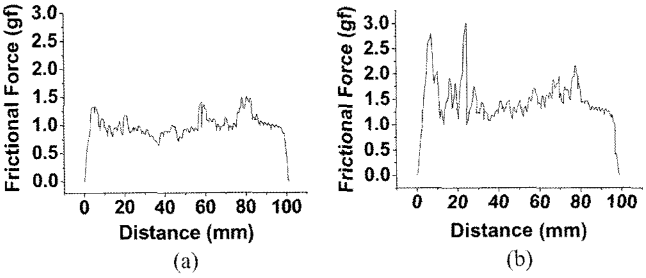


Fig. 6. Frictional force between small intestine and 6 mm diameter (a) solid cylinder, and (b) hollow cylinder at 2 gf normal load and 10 mm/s sliding speed.

Under the same experimental condition of normal load, sliding speed, and sliding distance as that of Fig. 5, frictional tests were performed for 6 mm diameter cylinder specimens shown in Fig. 3(b). Fig. 6 shows friction forces between the small intestine and 6 mm diameter solid and hollow cylinders. Hollow cylinder specimen in Fig. 6(b) shows relatively much higher frictional force of about 1.5 gf than the solid cylinder specimen (about 1.0 gf) in Fig. 6(a). In particular, the hollow cylinder shows a high frictional force at around 8 mm sliding distance that is about 2.5 times larger than the solid specimen.

For all cases tested in this work, the friction coefficient was in the range of 0.5 to 1.3 considering the instantaneous increase in the frictional force at various local points along the intestine specimen. This range of friction coefficient may be considered to be in the medium to high range compared with other frictional systems.

3.2. Friction generation mechanism of cylinder specimens

The frictional behavior of the 2 mm and 6 mm hollow and solid cylinder specimens sliding against the porcine small intestine surface may be described using the schematic shown in Fig. 7. The frictional force generation is due to a combination of mechanical interlocking and sliding friction on the flat bottom part of the cylinder specimen. The mechanical interlocking occurs at the outer boundary of the hollow cylinder in the case of the solid cylinders. In the case of the hollow cylinders, interlocking also occurs due to the protruding part of the intestine inside the hollow part of the cylinder. As for the sliding friction, it occurs due to contact between the flat portion of the cylinder bottom surface and the intestine surface.

It is interesting to note that the 6 mm solid cylinder has less frictional force than the 2 mm solid cylinder. Thus, it is clear that the frictional force between a solid material and the small

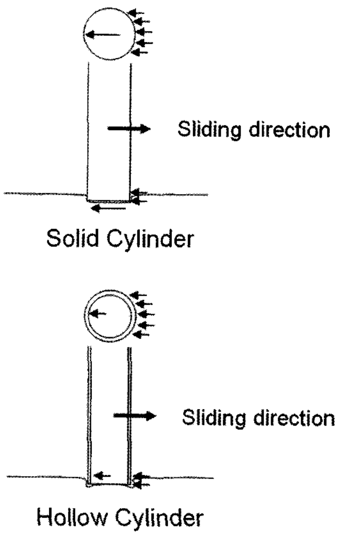


Fig. 7. Schematics of the frictional mechanism of solid and hollow cylinders.

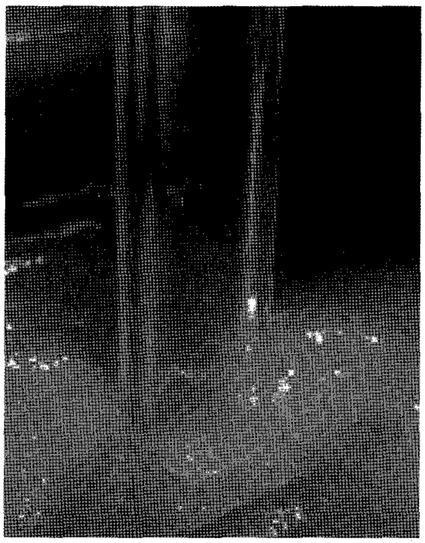


Fig. 8. Photograph which shows the effect of hollow cylinder on interlocking: 2 mm hollow cylinder does not show any protruding part of intestine at the center region.

intestine surface does not depend on the apparent contact area. This suggests that the interlocking effect produced by the intestine material surrounding the front edge of the cylinder specimen significantly effects the frictional force. It is apparent from the experimental result that the 2 mm solid cylinder specimen had greater interlocking effect than the 6 mm solid cylinder specimen.

As for solid and hollow cylindrical geometry, the major difference is in the protruding intestine at the center region of the hollow cylinder that is not present in the case of the solid cylinder. The degree of center protrusion is expected to depend on the inner diameter of the hollow cylinder. The photograph of the hollow cylinder in contact with the intestine specimen given in Fig. 8 shows that in the case of the 2 mm hollow cylinder, the protrusion is insignificant. Thus, the frictional mechanism for the 2 mm hollow cylinder is probably due to front region interlocking and some degree of sliding friction on the cross-sectional ring of the hollow cylinder. This resulted in the frictional force of the 2 mm hollow cylinder being less than the 2 mm solid cylinder.

When the 6 mm hollow and solid cylinders were tested, unlike the case of the 2 mm cylinder specimen, the hollow cylinder resulted in about fifty percent higher frictional force than the solid cylinder. This is perhaps due to the added interlocking effect of the protruded intestine part at the center region of the hollow cylinder. It can be postulated that the relatively larger inner diameter of the 6 mm hollow cylinder allowed the intestine tissue to bulge into the hollow section due to the compression at the rim of the cylinder.

The contribution of each friction mechanism cannot be clearly isolated from the experimental results. The frictional behavior seems to be dictated by a complex interplay of interlocking at different scales and sliding friction. Also, the intestine is known to have visco-elastic behavior and numerous works have been published on the complicated nature of the organ tissue [6-13]. Nevertheless, few insightful observations could be made from the experimental results obtained in the work. The interlocking mechanism of the cylinder specimens is analogous with the interlocking mechanism of the hookworm teeth interlocking with villi on the intestine surface. However, the interlocking of the hollow cylinder with the intestine surface occurs at a higher dimensional scale than the interlocking of the hookworm teeth with microstructures such as villi on the intestine. Therefore, these mechanisms should be described from a multi-scale point of view.

3. Summary

In this study, the interlocking mechanism of the hookworm teeth in contact with the small intestine surface was investigated using solid and hollow cylindrical specimens. The interlocking of the hookworm teeth was modeled as the interlocking and penetration actions of the cylindrical specimens against the small intestine surface. Different diameter solid and hollow cylindrical specimens were fabricated and used for the friction tests. The results are summarized as follows:

In 2 mm diameter specimen case, the solid and hollow cylinder specimens resulted in an average frictional force of about 1.5 gf and 1.2 gf, respectively.

In 6 mm diameter specimen case, the solid and hollow cylinder specimens resulted in an average frictional force of about 1.0 gf and 1.5 gf, respectively.

The friction coefficients for all the cylinder specimens sliding against the porcine small intestine were in the range of 0.5 to 1.3 including local variations in the frictional force.

The degree of interlocking effect depends on the solid/hollow geometry as well as the diameter of the cylinder. However, the degree of interlocking cannot be generalized for a given shape or diameter.

Acknowledgment

This research has been supported by the Intelligent Microsystem Center (IMC; http://www.microsystem. re.kr), which carries out one of the 21st century's Frontier R&D Projects sponsored by the Korea Ministry Of Commerce, Industry and Energy.

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