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Experimental investigation of frictional and viscoelastic properties of intestine for microendoscope application

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The information on the frictional resistance of a self-propelled robotic capsule endoscope moving inside the body is very important for the design and the performance enhancement of such parameters of the capsule endoscope as power consumption, motion control and positioning accuracy. Based on this motivation, the ultimate goal of this research was to develop an analytical model that can predict the frictional resistance of the capsule endoscope moving inside the living body. In this work, experimental investigations of the fundamental frictional characteristics and the viscoelastic behaviors of the small intestine were performed by using custom-built testers and various capsule dummies. The small intestine of a pig was used for the experiments. Experimental results showed that the average frictional force was 10–50 mN and higher moving speed of the capsule dummy resulted in larger frictional resistance of the capsule. In addition, the friction coefficient did not change significantly with respect to the apparent area of contact between the capsule dummy and the intestine, and also the friction coefficients decreased with an increase in the normal load and varied from 0.08 to 0.2. Such frictional behaviors could be explained by the lubrication characteristics of the intestine surface and typical viscoelastic characteristics of the small intestine material. Also, based on the experimental results, a viscoelasticity model for the stress relaxation of the small intestine could be derived.

KEY WORDS: biotribology, capsule endoscope, small intestine, stress relaxation, viscoelasticity

Nomenclature

F	Friction force (N)
μ	Friction coefficient
N	Normal force applied to the capsule (N)
$\sigma(t)$	Stress applied to the small intestine (Pa, N/m^2)
ϵ_0	Strain applied to the small intestine
t	Time (s)
E_1, E_2, E_3	Elastic modulus of spring (Pa, N/m^2)
η_1, η_2	Viscosity of fluid in dashpot (Pa s)

1. Introduction

Recently, wireless capsule endoscope has been developed and commercialized with the aid of the development of micro-fabrication technology [1–3]. It is expected that further development of a self-propelled robotic endoscope will make it possible to get samples for diagnosis and inject medicine into specific regions as well as image the internal organs [4–6]. From the viewpoint of the design of such a self-propelled capsule endoscope system, the information on the frictional resistance of the endoscope inside the internal organs is very important since the frictional resistance considerably affects its power consumption, moving mechanism and position control. Also, the mechanical response and deformation of the organs to the external force should be investigated to design and optimize the locomotion mechanism of the capsule endoscope. The ultimate goal of this research, therefore, is to establish an analytical model that can predict the frictional resistance of the capsule endoscope moving inside the internal organs, especially inside the small intestine. The reason for choosing small intestine among the internal organs lies in the fact that the small intestine is a main internal organ diagnosed by the capsule endoscope and the endoscope will experience relatively large friction when moving inside the small intestine since its inner space is relatively smaller than any other internal organs.

The prediction of the frictional force of the capsule traveling inside the small intestine can be obtained by using the information on the normal load and friction coefficient as shown in the following Amontons' basic friction law [7]:

$$F = \mu N \tag{1}$$

where F is frictional force, μ is friction coefficient and N is the normal load applied to the capsule endoscope. Figure 1 illustrates the process flow proposed in this work and the required information for frictional resistance prediction. The information on the actual normal force (pressure) exerted on the capsule and the friction coefficient of the capsule is needed. From the *in vitro* friction tests, fundamental frictional characteristics of the capsule moving inside the body with respect to

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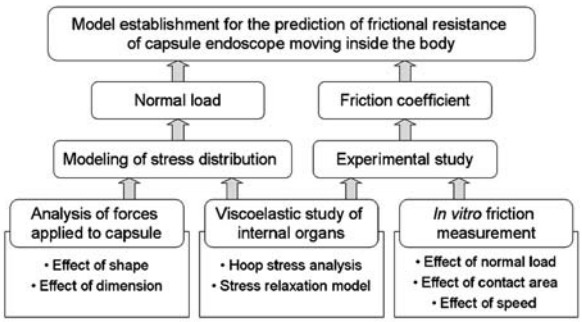

Figure 1. Objective and approaches of this research.

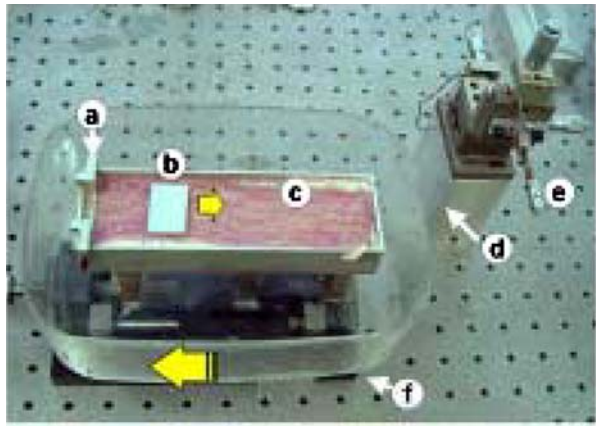

Figure 2. Bio-tribotester for frictional force measurement. (a, Specimen holder; b, capsule or block dummy; c, a cut-open small intestine specimen; d, wire; e, force sensor part; f, heat reservoir and transportation stage.) The large arrow shown in the bottom of figure indicates the moving direction of the transportation stage including the intestine specimen, while the small arrow beside the capsule dummy indicates the relative moving direction of the capsule dummy that is being pulled.

various parameters can be collected. Also, the viscoelasticity test provides the important information on the stress–strain relationship and the stress relaxation characteristics of the internal organs, which are closely related to the frictional resistance. If the range of variation in the friction coefficients of the capsule moving inside the internal organs and the normal load (or pressure) applied to the capsule surface can be obtained according to the capsule geometry and the moving speed, it is possible to predict the frictional resistance of the capsule that travels inside the living body.

In the previous experimental study on the frictional resistance of a capsule inside the small intestine of a pig with respect to various capsule shapes, it was found that the smooth cylindrical capsule showed the least frictional resistance due to the absence of edge effects and the frictional behavior of the capsule reflected the magnitude of the circumferential force induced by the viscoelastic deformation of the small intestine [8]. Based on the result, this work focused on the experimental investigation of the variations in the friction coefficients of the smooth cylindrical capsule with respect to moving speed, weight (or load) and surface area of the capsule. In addition, in order to predict the force applied to the capsule moving inside the small intestine, the stress–strain relationship was investigated systematically via stress relaxation test of the small intestine. In this work, the small intestine of a pig was also used for experiments because its features are quite similar to those of a human intestine. In fact, it is believed that the organs of the pig will be most suitable for human transplantation, since the pig has close internal anatomical similarity to the human body [9,10]. The following sections give the details of the experiments.

2. Experimental details

2.1. Measurement of the frictional resistance of a capsule

2.1.1. Bio-tribotester

Frictional resistance of a capsule was measured by using a custom-built bio-tribotester shown in figure 2. Frictional force was measured while the capsule was being pulled inside or on the intestine specimen by a fixed flexible beam. For frictional force sensing, a series of semiconductor strain gages mounted on the beam were used. The moving speed of the capsule was controlled using a motor controller and the speed range was between 0.16 and 0.5 mm/s, which corresponds to the average speed of peristalsis [11,12]. The conditions of the intestine specimen such as pH level (7.4–7.8) and temperature (36.5 °C) were set to be similar to a human intestine.

2.1.2. Capsule specimens

In order to observe the variations in the frictional resistance according to the weight (or normal load) and the apparent contact area of the capsule, two groups of aluminum blocks with various sizes were designed and fabricated (see figure 3(a)). Since the previous study showed that the frictional resistance of a capsule inside the intestine was not largely affected by the capsule material [8], aluminum that has relatively good machinability was selected as the specimen material for this study. Basically, the objective of these experiments was to determine the general friction characteristics of the small intestine. When a block travels inside the intestine, the block expands the intestine and thus induces circumferential stress (or hoop stress) in the intestine wall since the original small intestine has a tube form, as shown in the previous research [8]. Therefore, to remove the effect of hoop stress and thereby to observe the effects of weight and contact area more clearly, frictional force was measured while the block was being pulled on a cut-open intestine specimen, as

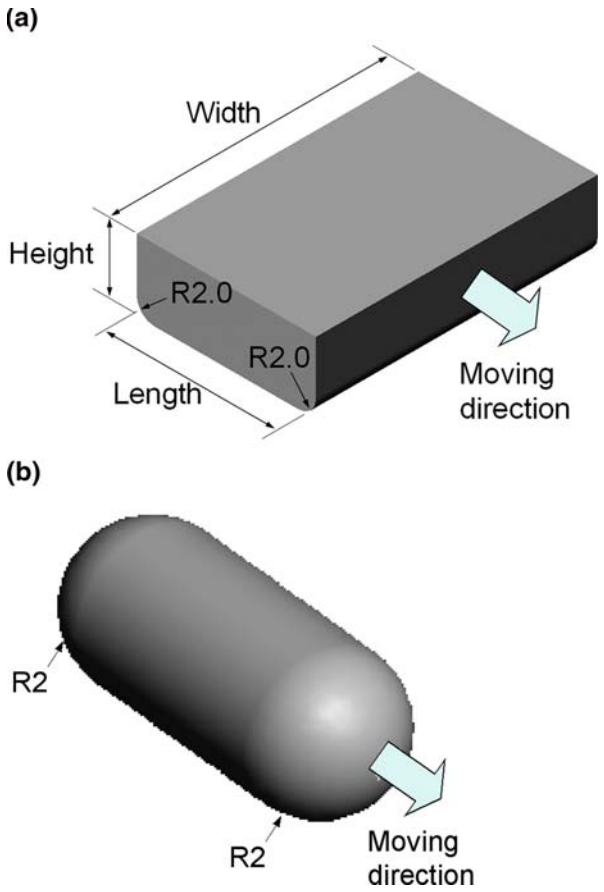

Figure 3. Block and capsule specimens for friction test.

shown in figure 2. Table 1 summarizes the specifications of the blocks of group A called a1–a5, which were designed to investigate the effect of normal load. Therefore, the bottom areas of all of these blocks, which are in contact with the intestine wall, are equal but the weights of them are totally different. On the contrary, the blocks of group B (b1–b5) with the same weights and different bottom areas were fabricated in order to observe the effect of contact area, as presented in table 2.

In another set of experiments designed to investigate the effects of moving speed and diameter of a capsule on the frictional resistance, the smooth cylindrical capsule dummies with various diameters were fabricated in aluminum (see figure 3(b)). Table 3 summarizes the details of the capsule specimens. In these tests, the capsule was pulled inside the small intestine in order to observe the effect of the expansion of the intestine wall induced by the capsule diameter on the frictional resistance.

Table 2.
Details of the blocks of various contact areas – group B.

Group B	b1	b2	b3	b4	b5
Height (mm)	15.3	10.2	7.7	6.1	5.1
Width (mm)	31.4	31.4	31.4	31.4	31.4
Length (mm)	20.0	30.0	40.0	50.0	60.0
Contact area (mm^2)	502.4	816.4	1130.4	1444.4	1758.4
Weight (mN)	252.8	252.8	252.8	252.8	252.8

The weights and dimensions of the blocks and capsule dummies were chosen based on the specifications of the capsule endoscopes that have been commercialized or are under development [2,4].

2.2. *Measurement of the stress relaxation of the small intestine*

As mentioned above, the intestine wall expands or contracts in the radial direction of the cross-section of the intestine when a capsule moves inside the small intestine and accordingly, the stress induced by the viscoelastic deformation of the intestine is applied to the capsule. The stress applied to the capsule will be considerably different according to the variation of the capsule diameter as well as the moving speed of the capsule. In order to predict the frictional resistance of the capsule, it is essential to understand quantitatively the force–viscoelastic deformation characteristics of the small intestine. Therefore, the stress relaxation test [13,14] of the small intestine was performed using a special set-up and also the viscoelasticity modeling of the small intestine was carried out, based on experimental results.

Figure 4 shows the experimental set-up for stress relaxation test of the small intestine. Both ends of the small intestine specimen were held by the upper holder fixed to the beam and the lower holder which could move up and down along the guide, as shown in the figure. As the eccentric wheel was rotated using a step motor, the intestine specimen extended and then at fixed elongation length, the force sensor mounted on the beam, according to time, measured the force induced by the deformation. By using the eccentric wheel, a sinusoidal displacement could be obtained, which was

Table 1.
Details of the blocks of various weights – group A.

Group A	a1	a2	a3	a4	a5
Height (mm)	2.5	6.8	11.0	15.3	19.5
Width (mm)	31.4	31.4	31.4	31.4	31.4
Length (mm)	20.0	20.0	20.0	20.0	20.0
Contact area (mm^2)	502.4	502.4	502.4	502.4	502.4
Weight (mN)	40.2	111.7	181.3	252.8	322.42

Table 3.
Details of the capsule dummies of various diameters

Type	A	B	C	D
Diameter (mm)	10.0	9.0	8.0	7.0
Length (mm)	20.0	20.0	20.0	20.0
Front and rear fillet (mm)	R2.0	R2.0	R2.0	R2.0
Weight (mN)	40.2	32.3	25.5	19.6
Surface area (mm^2)	727.9	640.6	556.5	475.5

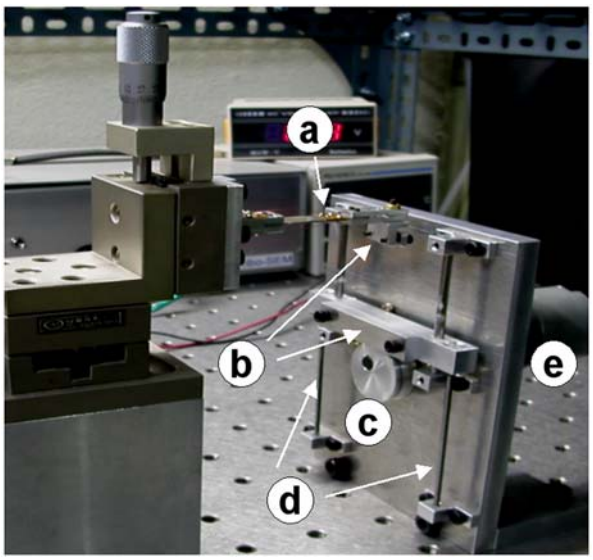

Figure 4. Experimental set-up for stress relaxation test of the small intestine specimen (a, force sensor; b, specimen holder; c, eccentric wheel; d, spring; e, step motor).

similar to the deformation of the intestine observed when the cylindrical capsule passed along the intestine. Maximum speed and length of elongation using this set-up were about 20 mm/s and 10 mm, respectively.

Table 4 summarizes the average dimensions of the small intestine before and after inserting a capsule with 10 mm diameter. From the value, it is found that the initial circumferential length of an intestine specimen before capsule insertion is about 45 mm and the strain in circumference of the small intestine induced by the capsule insertion measured 0.16 (16%). Based on this information, in the stress relaxation test, the initial length of a cut-open intestine specimen was set to 42 mm excluding the parts gripped by the sample holders and the elongation lengths for relaxation test were chosen from 3 to 10 mm.

3. Experimental results of the frictional resistance of a capsule

3.1. Effect of normal load

Figure 5 presents the frictional resistances of the blocks with various weights moving on a cut-open intestine specimen. It shows that according to the increase in the normal load, frictional force increases but on the contrary, the friction coefficient decreases from 0.2 to 0.08. Such a decrease in the friction coefficient can be explained by understanding the surface state of the small intestine. The internal surface of the small intestine is covered with water and secreting juice, which can act as a lubricant [11]. When relatively high normal load is applied on the intestine surface, the surface is squeezed and thus the amount of the juice and water increases. Therefore, the lubrication effect increases and consequently friction coefficient becomes lower. It can also be thought that the friction inside the living intestine may be much less than the result presented in this work, since the amount of the secretory juice is definitely larger in the living tissue.

Table 4.
Radial expansion of the intestine after a 10 mm dia. capsule insertion.

10 mm diameter capsule	Small intestine of a pig		
	Inner diameter (mm)	Outer diameter (mm)	Wall thickness (mm)
Before insertion	7.8	14.3	3.3
After insertion	10.0	15.6	2.8

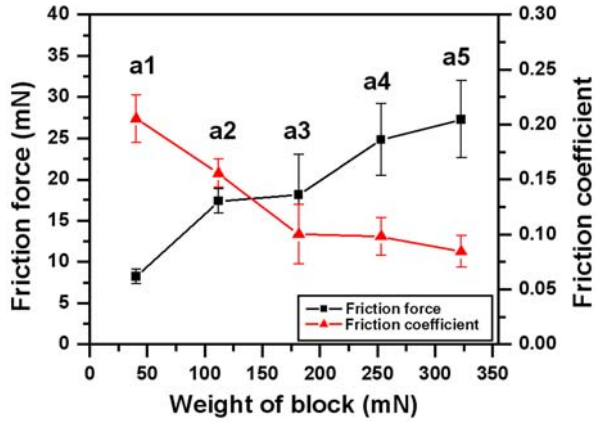

Figure 5. Frictional forces and friction coefficients of the aluminum blocks with various weights.

3.2. Effect of contact surface area

Figure 6 shows the effect of contact surface area on the frictional resistance. The result shows that frictional force does not change significantly with respect to

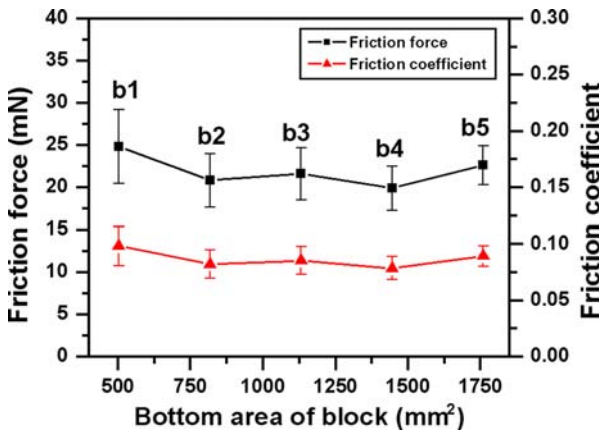

Figure 6. Frictional forces and friction coefficients of the aluminum blocks with various contact surface areas.

various surface areas. This result indicates that the surface area of the capsule does not need to be considered for the capsule design from the tribological viewpoint. In the previous experimental work performed using the capsules of various shapes even with corrugations or sharp corners, it was concluded that the increase in the frictional resistance of the capsule depends on the increase in the contact area between the surface grooves and the intestine tissues in addition to the effect of the capsule corners [8]. In the work, for capsules with relatively sharp edges, the frictional force was relatively high at the initial stage and also, the frictional force for the capsules with corrugations was about two times higher than the capsule with a smooth cylindrical shape. However, the relative significance of the surface area and the edge effects on the capsule frictional resistance has not been understood clearly from the results, since the effects of these two factors appeared simultaneously. Both the surface area and the edge of the capsule (surface geometry) would contribute to the frictional resistance at micro-scale because the surface area is established in true contact area and the edge of the capsule induces locally large variation of frictional resistance. Considering the results of this work together with such previous results, it can be concluded that the frictional resistance of a capsule moving inside the small intestine is mainly dependent on the interaction between the intestine wall and the surface geometry of capsule, not the interaction between the intestine wall and the contact surface area of capsule.

3.3. *Effect of speed*

The frictional resistances of the capsules with various diameters according to the moving speed inside the small intestine are presented in figure 7. The data shows that as the diameter and moving speed of a capsule increase, the frictional force of the capsule also increases. Especially, such an increase in friction at higher speed appears more clearly in the capsule with larger diameter. This relationship between the capsule speed and frictional resistance can be explained by using the viscoelastic characteristics of the intestine specimen [15,16]. In other words, when the capsule speed is lower, the deformation of the intestine wall induced by the capsule generates more slowly and also the stress relaxation of the intestine occurs more during the capsule passage. Therefore, such stress relaxation leads to lower frictional force. The following section describes the stress relaxation characteristics of the intestine in detail.

4. Stress relaxation of the small intestine

4.1. *Experimental result of the stress relaxation test*

The experimental result of stress relaxation test is presented in figure 8, which shows typical stress relaxation behavior of viscoelastic material. This result explains the increase of the frictional force according to the moving speed and diameter of the capsule. Thus, the data demonstrates that once the intestine gets deformed and stressed, the stress in the intestine lasts quite long and is larger as the circumferential elongation increases. This means that if a capsule with larger diameter moves faster inside the intestine, the stress generated by the capsule passage is much higher and remains longer and consequently the frictional resistance of the capsule would increase.

4.2. *Viscoelasticity modeling of the small intestine*

Based on the experimental result of the stress relaxation, the relaxation model of the small intestine was made for the purpose of the prediction of

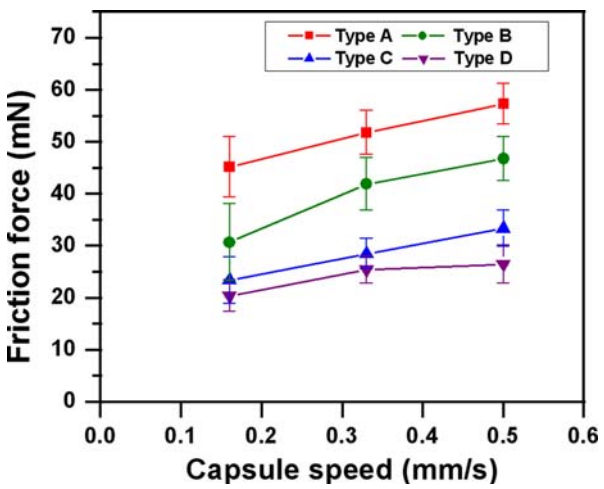

Figure 7. Frictional forces of the capsules with different diameters with respect to various speeds.

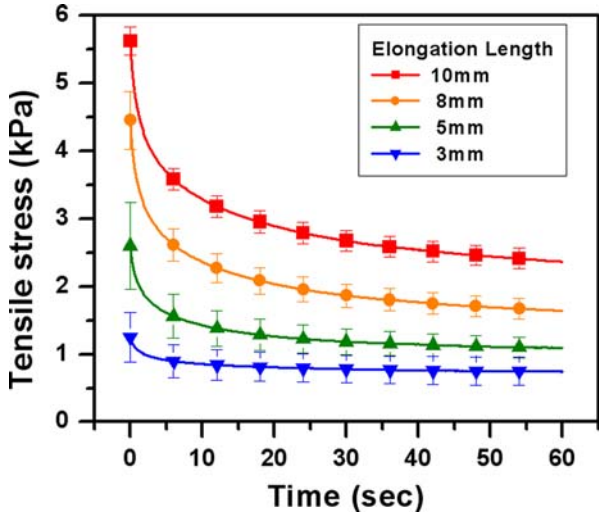

Figure 8. Stress relaxation of the small intestine specimen according to the circumferential elongation length.

mechanical response of the small intestine to the external force.

In general, for the description of the viscoelastic behavior of a material, a four-element model or a generalized model with more elements is used [16–18]. In this work, in order to fit the experimental result of figure 8, a five-element model was introduced for stress relaxation model of the small intestine, as shown in figure 9. This viscoelasticity model for stress relaxation can be expressed as the following equation:

$$\sigma(t) = \varepsilon_0[E_1 \exp(-t \cdot E_1/\eta_1) + E_2 \exp(-t \cdot E_2/\eta_2) + E_3] \quad (2)$$

where, E_1, E_2 and E_3 indicate the elastic moduli of springs and η_1, η_2 are the viscosities of dashpots shown in the model schematic. Also, ϵ_0 is the constant strain applied to the intestine for the relaxation test. For example, in the case of 10 mm elongation in the relaxation test, the value of ϵ_0 is about 0.24 ($=10.0/42.0$).

Table 5 presents the values of each element in the stress relaxation model obtained from non-linear curve fitting with respect to the experimental result of strain 0.16 which is the strain value generated in the intestine by inserting a capsule with 10 mm diameter, as shown in table 4. Therefore, equation (2) can be expressed as the following equation with the values of each element.

$$\sigma(t) = 0.16[7.0 \exp(-t/18.0) + 6.3 \exp(-t/1.6) + 9.2] \quad (3)$$

The comparison of the results between the model and the experiment of the stress relaxation is presented in figure 10. Here, the experimental data of strain 0.16 was obtained from the experimental data of each strain, which were presented in figure 8. In other words, to reduce the measurement error from the stress relaxation experiment and get more reliable data of strain 0.16, the experimental data of each strain were converted to the data of strain 0.16 and then were averaged. Figure 10 shows that the model corresponds well to the experimental results and shows the coincidence of more than 99%.

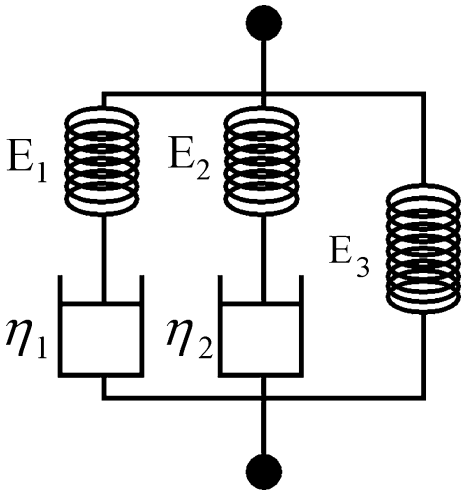

Figure 9. Viscoelasticity model for stress relaxation of the small intestine.

Table 5.
Elements of a stress relaxation model.

Relaxation model	Value
E_1 (KPa)	7.0
E_2 (KPa)	6.3
E_3 (KPa)	9.2
η_1 (KPa s)	125.9
η_2 (KPa s)	10.3

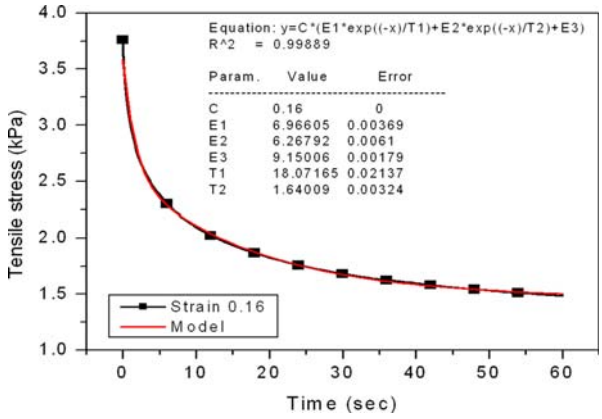

Figure 10. Comparison of the results between the experiment and the model of the stress relaxation.

Another viscoelastic model with different number of elements may be used as a viscoelastic model of the small intestine specimen. In fact, efforts were made to find out how many elements are needed at a minimum in order to fit well to the experimental result. Figure 11 shows a four-element model that was established from Maxwell model and its fitting result to the experimental data of strain 0.16. As can be seen in the figure, in the case of the models with less than five elements, it was found that relatively low coincidence (about 96%) between the model and the experimental result was obtained and the model did not fit well to the experimental data. Based on the result, therefore, the five-element model was chosen as a viscoelastic model for the small intestine.

This viscoelasticity equation (3) of the small intestine can be used to analyze the distribution on the intestine wall of the stress induced by the capsule moving inside the intestine and thereby the normal load distribution exerted on the capsule surface can be obtained. In the end, the frictional resistance of a capsule can be predicted by using this method. The process for the establishment of a numerical prediction model is described elsewhere [19].

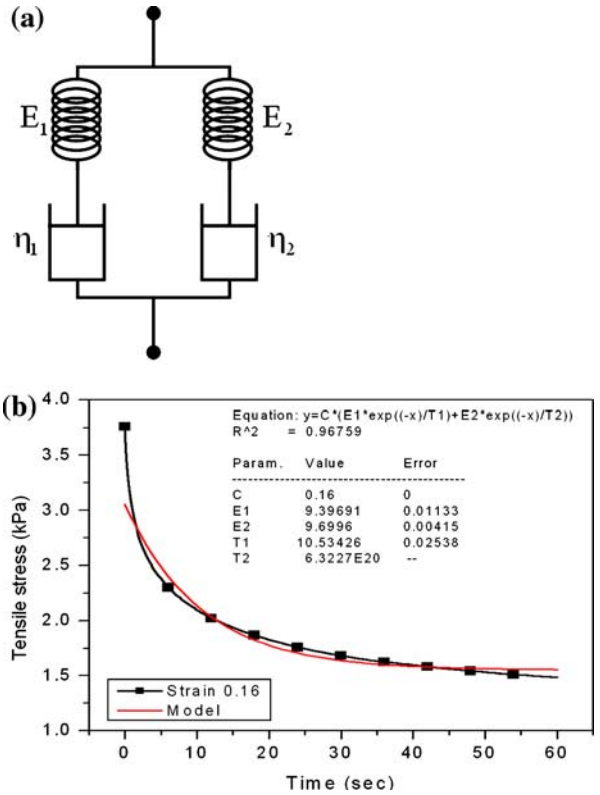

Figure 11. A four-element model of the stress relaxation: (a) schematic of a four-element model, and (b) comparison of the results between the experiment and the four-element model.

5. Conclusions

In this work, as the basic steps to establish a model for predicting the frictional resistance of the capsule endoscope, the frictional characteristics of the capsule endoscope moving inside the small intestine were investigated using a custom-built bio-tribotester with respect to the normal load, contact area and moving speed. Also, the stress relaxation test was conducted to understand the viscoelastic characteristics of the small intestine of a pig. From the results, it was found that the friction coefficient decreased with the increase in the normal load and varied from 0.08 to 0.2. In addition, the frictional resistance of a capsule moving inside the small intestine was mainly dependent on the interaction between the intestine wall and the surface geometry rather than the surface area. Experiments on the effects of moving speed and diameter of capsule revealed that the frictional force of the capsule also increased as the diameter and moving speed of capsule increased. These frictional behaviors could be explained by understanding the surface state and the viscoelastic characteristics of the small intestine. Thus, the result from the stress relaxation test using a specially designed experimental set-up suggested that if a capsule with larger diameter moves faster inside the intestine, the stress generated by the capsule passage would be much higher and remain longer and consequently the frictional resistance of the capsule would increase. Also, a viscoelasticity model for the small intestine of a pig could be derived, based on the stress relaxation result. It is expected that this model can be used effectively for the design optimization of the capsule locomotion mechanism.

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